Bachelor’s Thesis

Bachelor's degree in Industrial Technology Engineering

Design and operation of a hybrid power system for Menorca

REPORT

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Abstract

This project consists on the design of a power system based on renewable sources for the island of Menorca. The main objective of this design is to make the power system of the island as renewable as possible. To do so, there have been selected photovoltaic (PV) and wind power as the main renewable sources, non-renewable sources considered are fuel (case 1) or a cable that connects Menorca to Mallorca and provides energy from the peninsula (case 2), the system will also include batteries.

First, there is an energetic study of how much power can be obtained from each source. Then, the methodology used to study the system is by simulation and later optimization. The simulation includes two parts, an energetic and an economic one, and returns the desired parameters given a system configuration defined as the number of PV modules, the number of wind turbines, and the battery capacity in MWh. The energy-based simulation obtains the distribution of power for each source and the % of renewable energy consumed, among others. The economic simulation, inspired by the Levelized Cost of Energy (LCOE), returns the cost per MWh of energy consumed.

The optimization objective is finding the system configuration that provides the highest % of renewable energy and the lowest costs per MWh. To do that there has been used an indicator defined as the cost per MWh divided between the % of renewables, and to minimize it. There has been established a maximum of exceeding energy (that is produced in excess and won't be used), and stability restrictions are not taken into account. After that, there has been carried out a sensitivity analysis to know how the results obtained previously may change in the future according to the cost trends of the sources.

Results show that the % of renewables is in all situations more than 60%, the exact value and the average cost of generation depends on the costs of all the components of the system. When the non-renewable source is much more expensive than the renewables, the average cost increases and the % of renewables also highly increases; while when costs of renewables and non-renewables are more similar, it led to situations with lower average costs and lower penetration of renewables. Future situations predict an increase in the % of renewables, and in most of the cases the average costs will be reduced.

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List of acronyms

PV	Photovoltaic
DC	Direct current
AC	Alternating current
REE	Red Eléctrica de España
PERC	Passivated Emitter Rear Cell
IEC	International Electrotechnical Commission
CapEx	Capital Expenditures
OpEx	Operational and Maintenance Expenditures
LCOE	Levelized Cost of Energy
LCOS	Levelized Cost of Storage
$LCOE_m$	Levelized Cost of Energy modified
NREL	National Renewable Energy Laboratory

1. Preface

1.1. Project's Origin

The energy transition is defined as a long-term structural change in energetic systems. Nowadays, this term is been used as a component in the fight against climate change and a way to achieve a more sustainable future. It is a worldwide subject that has appeared in several meetings and international conferences. In that context, Europe's target is to generate 20% of energy by renewable sources by this year, and 32% by 2030 [1]. In Spain, the objective for 2030 is to generate 42% of energy by renewable sources. Specifically in the electrical sector, the renewable generation target is 74% by 2030, to achieve the final objective of 100% renewables in 2050 [2]. According to statistics, in Spain 38.4% of electric energy generated in 2018 was from renewable sources [3], but its distribution is variable throughout the territory.

Microgrids have a significant role in the energy transition. A microgrid is defined as a group of loads and energetic sources that works as a controllable single unit, and it can be connected to the general grid or be isolated. Microgrids allow the generation to be closer to the loads, being able to increase energy self-sufficiency and effectively integrate various sources of distributed generation. The size of a microgrid can vary from a community of a few customers to all the population of an island.

The Balearic Islands are an archipelago of Spain in the western Mediterranean Sea, near the eastern coast of the Iberian Peninsula. It is formed by Mallorca, Menorca, Cabrera, Ibiza, and Formentera. The islands have suffered a high population growth due to tourism, receiving more than 9.8 million foreign tourists annually. A characteristic of the Balearic Islands power system is that it is connected to the national grid through an undersea cable that connects Mallorca to Valencia (on the peninsula), and, the same way, Menorca and Ibiza-Formentera are connected to Mallorca. This allows the peninsula to provide a significant amount of energy to the islands, enhancing the security of energy supply on the islands and avoiding sudden power outages.

This project is focused on the case of Menorca, the third most populated island in the Balearic Islands. Given its characteristic situation of fossil fuel generation and its isolation to the other islands, it is an interesting place to realize a new power system. In addition, it has been selected as one of the few European islands to start a project of the energy transition. In this project, the microgrid size is defined as the whole island.

1.2. Motivations

Climate change has been positioned as one of the biggest crises to face, and one of its many facets is energy generation and consumption. Renewable energy has been increasingly used in electricity generation, but is it enough?

The author has a special interest in applying renewable energies to make a system as renewable as possible. So it is very interesting to study technologically how far can a system go, while taking into account the economic aspect. In previous projects, the author studied a system with big consumption and very limited space to generate energy, here the novelty is to study a system without space restrictions.

2. Introduction

Menorca is one of the Balearic Islands, located in the Mediterranean Sea. Compared with other Spanish islands, Menorca is not very big (700 km^2) and does not have much population (95000 in 2018), although in summer its population doubles due to tourism. In 1993 Menorca was declared Biosphere Reserve by UNESCO.

Figure 2.1: Configuration map of the energetic system of Menorca [1]

Following the European and Spanish targets of becoming more sustainable, the Balearic Government approved in January 2019 a roadmap so that 85% of Menorca's energy consumption comes from renewable sources by 2030. To do so, it is planned to have 300 MWp of photovoltaic power, 10 MW of wind power, 30 MW of self-consumption photovoltaic power, and 650 MWh of storage in batteries [11]. The final infrastructure will produce until 70 MW in winter so part of that production may supply Mallorca [12]. That project will require around 600 million euros. Menorca has a long way to reach that goal, because nowadays only 5% of energy consumed comes from renewable sources.

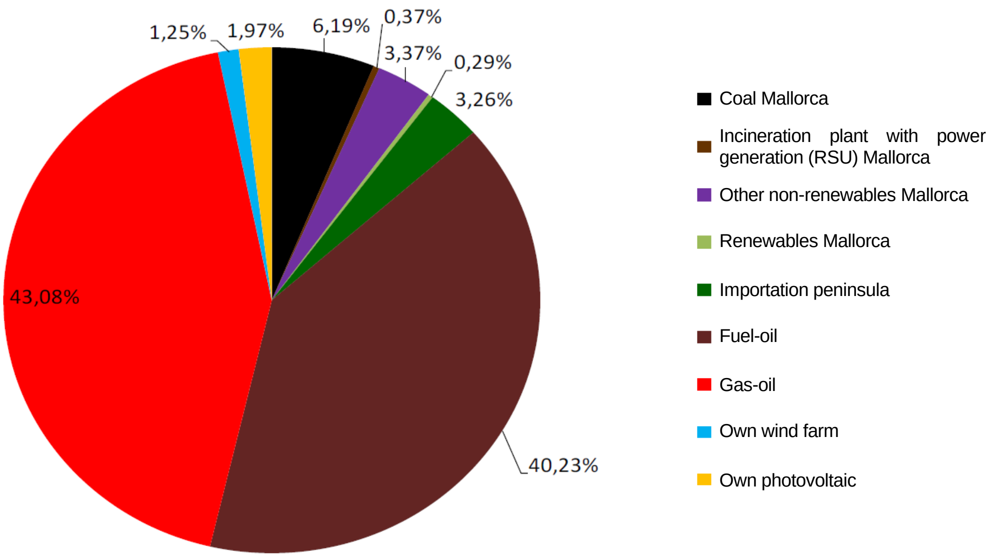

Figure 2.2: Electricity in Menorca in 2013 by source [4]

This project is focused on exploring the possibilities of making Menorca a more renewable island in terms of energy management. Maybe a 100% renewable is difficult to achieve, but the current situation cannot continue and there are a lot of ways to improve. By searching for a solution with more renewable energies, Menorca will reduce its pollution level and would reduce its dependence on external input of energy due to the self-production. Which will lead to an increase of the quality of life of its population. Also the economic impact of this change may be positive because nowadays electric energy in the Balearic Islands is much more expensive to obtain than in the peninsula.

2.1. Objectives of the project

This project addresses the design of a power system based on renewable sources for the island of Menorca. The main objective of this design is to make the power system of the island as renewable as possible, fixing an approximate goal of 85% of renewable energy consumed. To do it, the steps to follow are:

- Study of possible power sources and load profile of the location
- Energetic analysis of generation versus consumption
- Simulation of the system
- Optimization of the system taking into account technical and economic aspects

The final system must be defined by the power for each source and storage capacity, if needed. It should also be mentioned the relationship between Menorca and other islands or the rest of Spain in terms of energetic collaboration or isolation.

2.2. Scope

The study system consists of a single energy consumption corresponding to the total of the island, which must be supplied with different power sources, focusing on renewables but also considering non-renewable sources already in use. The renewable power sources considered are PV and wind power, and the non-renewable sources are fuel (diesel) and cables with Mallorca, the system will also have batteries. Each power source should be studied independently at first, with its advantages and its limitations, assuming that some considerations need to be made to facilitate data processing. PV power is considered to be centralized, but distributed power can be also studied in future projects.

At the simulation, all the power sources must be taken into account and the results should show how each power source interacts with the rest of the system. There will be an analysis that combines: energetic (technical) and economic perspective. The energetic analysis describes the amount of consumption is supplied by each power source, and economic analysis will indicate the cost of the system. In the energetic analysis, there have not been considered system losses, and neither dynamic systems. To facilitate the economic analysis, it has been considered that the installation is done at once; a progressive installation would require a separate study.

In the optimization, the objective is to find the configuration of the system that provides the highest amount of renewable energy and the lowest cost. Due to a large amount of data to process, the computer might take some time to process it. For that reason, data processing will be programmed and automated as much as possible, using is Excel and Matlab software.

The main focus of the thesis is in the technical aspect, for that reason energetic analysis will be done in-depth. An economic analysis will also be done because it has significant importance in the implementation of this kind of project. But due to the load that the project represents and the amount of time to spend on it, economic analysis will be done more superficially and the parameters will be highly based on bibliography. To reduce the possible error and quantify the validity of the system there should be done a sensitivity analysis of the economic parameters, which allows to evaluate multiple points.

A relevant limitation of the analysis is the power system stability. When introducing a new generation, it is important to assure that the power system will remain stable (for example the fact that inverters do not have inertia influences negatively the frequency stability [5]). All these considerations would be dynamic and frequency restrictions to the system of study, but on this thesis they are not taken into account. Realizing the whole study of the system without those restrictions is the main scope limitation for the obtained results. This thesis can be complemented with stability simulations and other future studies.

3. Technical background

3.1. Menorca

Nowadays Menorca has several sources of energy. The Maó thermal power plant has been the main source of energy on the island for several years, with a production of 477.6 GWh on 2019, it uses fuel-oil and gas-oil almost in equal parts [7]. The electric connection Mallorca-Menorca by sea-cable broke in 2016 and the new one ended its construction in November 2019 but will not start working till autumn 2020, this cable has a capacity of 100 MW and will supply 30 MW to meet the security criteria. Menorca also has renewable sources, photovoltaic energy and wind power represented 1.97% and 1.25% (respectively) of the total energy generation [6]. Renewable sources have been slowly penetrating the power system of the island (Figure 3.1), but currently they still insignificant compared to non-renewables (Figure 3.2).

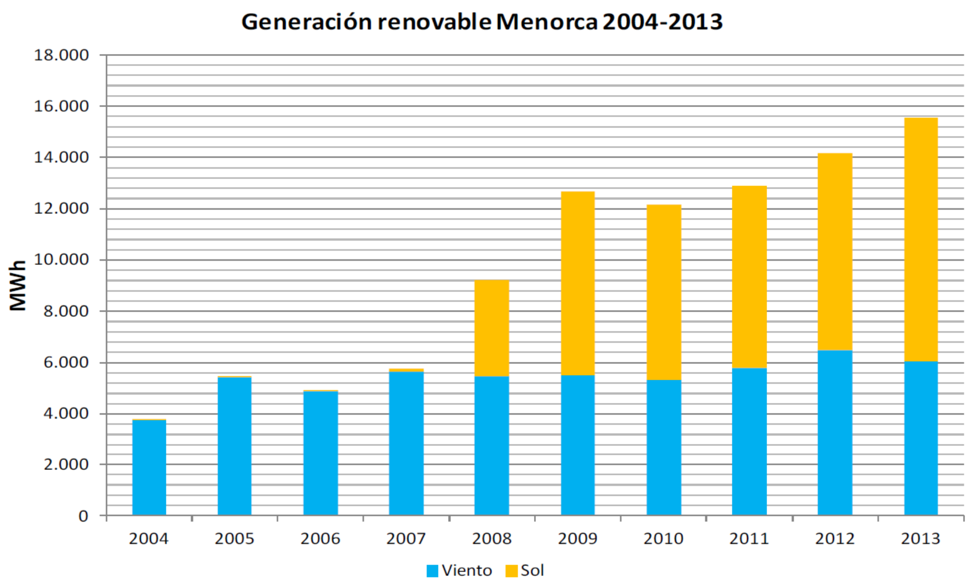

Figure 3.1: Evolution of renewable energy production in Menorca (wind and sun) [4]

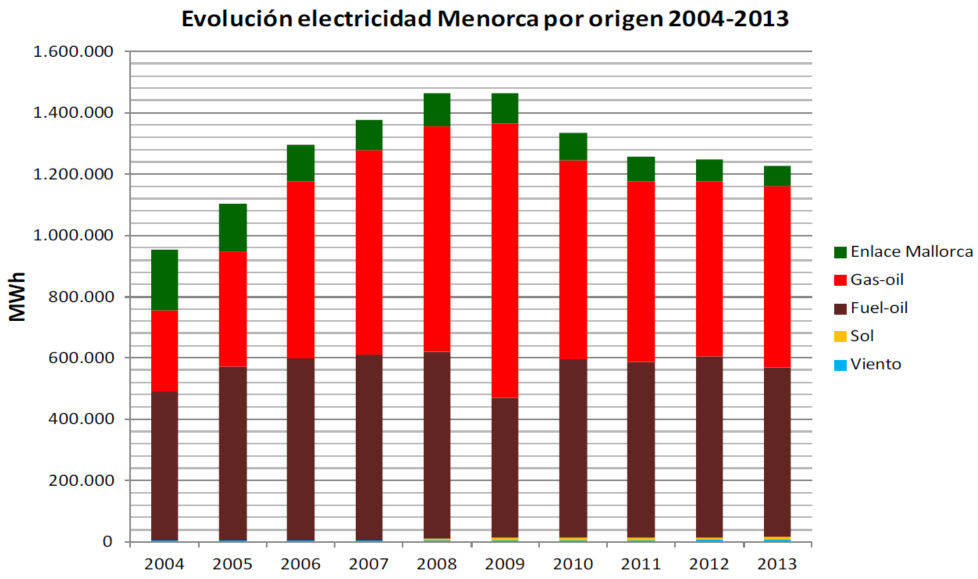

Figure 3.2: Evolution of the production and obtention of electric energy in Menorca by energy vectors (connection with Mallorca, gas-oil, fuel-oil, sun, wind) [4]

With this distribution of energy, the mean cost of energy generation in the Balearic Islands is around 145 €/MWh [8] whereas on the peninsula it is around 45 €/MWh [9].

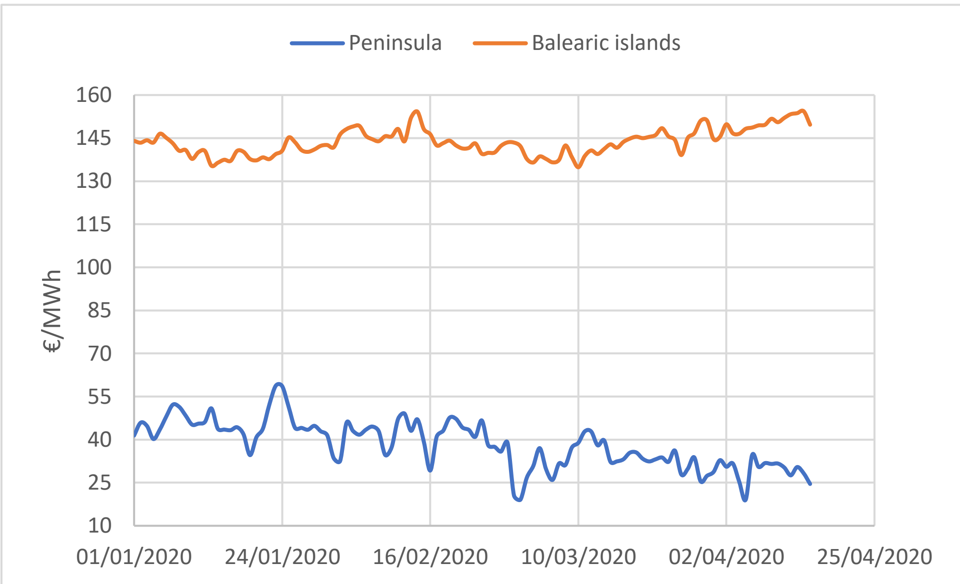

Figure 3.3: Average cos of generation in the peninsula and the Balearic Islands [10]

3.2. Photovoltaic power

Photovoltaic (PV) power is a renewable energy source that produces electricity with solar radiation by a photovoltaic cell. In Annex A can be found a detailed explanation of how photovoltaics work, the materials used and its environmental impact.

To increase the amount of energy that arrives at the cells of the PV modules, it should be as best oriented to the sun as possible. To do that, there are two main parameters: azimuth and slope. Azimuth is the direction in which are oriented the PV panels; to the south is 0º, to the east is -90º, to the west is 90º, and to the north is 180º. The slope is the angle that the PV modules form with respect to the horizontal, 0º is horizontal and 90º is vertical.

In addition to the solar panels, the other important components in a PV system are the inverters. The solar panel or PV module contains the PV cells and has an output of direct current (DC). Inverters convert DC to alternating current (AC) and are essentials to connect most electric devices and connect with the electrical grid, inverters are the most expensive component. Racking refers to the structure that fixes the solar array to the ground or rooftop, they are typically constructed from steel or aluminium. This structure can place the PV modules in flat or inclined (with respect to the ground). Some racking systems also incorporate tracking systems that use motors and sensors to track the Sun across the sky, increasing the amount of energy generated at a higher cost of equipment and maintenance. Other system components are combiners, wiring, disconnects, breakers, meters, and other protections (such as fuses) [13].

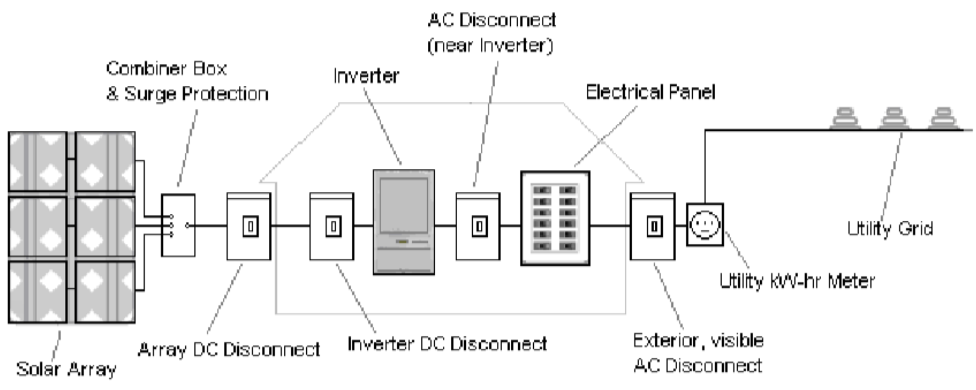

Figure 3.4: Configuration and components of a PV system connected to the grid [74]

Concerning the generation distribution, PV energy has a large income during sunny hours but after that, it does not produce anything, the grid should balance generation with consumption. For systems with high penetration of PV energy into the grid, there have been stability issues that affect both the steady-state performance and the transient stability of the grid [14].

PV generation can form different systems according to its size and distribution Centralized power plants, here named photovoltaic power stations, work at utility-scale which consists of more than 1 MWp and they are designed to supply power into the grid. This type of generation is characterized to be on large land extensions, power is generated there and then is distributed using the grid. As opposed, decentralized solar power systems are small-scale, and are a commercial (around 1 MWp) and residential (some kWp) use. These systems are located on-site, reducing to the minimum transmission losses of energy, and can be placed on rooftop.

In order to maximize production possibilities and involve the local population, as long as it is possible, power generation should combine both systems mentioned previously. Rooftop PV can be very useful in cities with high demand of electricity, since one part of it can be self-consumption. Since the total production should supply a certain demand, installing rooftop PV allows to reduce the extension of land used for the photovoltaic power station, which means less visual impact on that area and its environmental impact.

For the case of Menorca, Ciudadella and Maó are the main population centers and they are located in opposite sides of the island, but other cities can be also taken into account to distribute power. From the built-up area of the island [15] there can be calculated the approximate amount of distributed energy production [16], which for Menorca it would be around 100 MWp.

PV power is very popular for various reasons. On one hand, it is a mature technology, widely expanded on the market and easy to access. On the other hand, it is easy to make the investment in several terms, because the modules can be brought separately and even with comparatively little initial investment the installation will start operating. Despite this, PV power will not usually run in stand-alone systems, so it is generally used in hybrid systems that offers better economic results.

3.3. Wind power

Wind energy is a renewable energy source that uses the kinetic energy of air masses (wind) to produce electricity. In Annex B can be found a detailed explanation of how wind turbines work, the types of turbines and its environmental impact.

A wind farm is a group of wind turbines in the same location, it can be both on-shore and off-shore. The success of this power plant is determined by the location and its wind conditions, access to electric transmission, physical access, and local electricity prices. Then, in the design stage, the important factor is the space between the turbines; having to balance from a situation where the turbines are so close that they block wind from each other, to a situation where the turbines are so far apart that the costs of roads and cables increase a lot, also the amount of land needed increases.

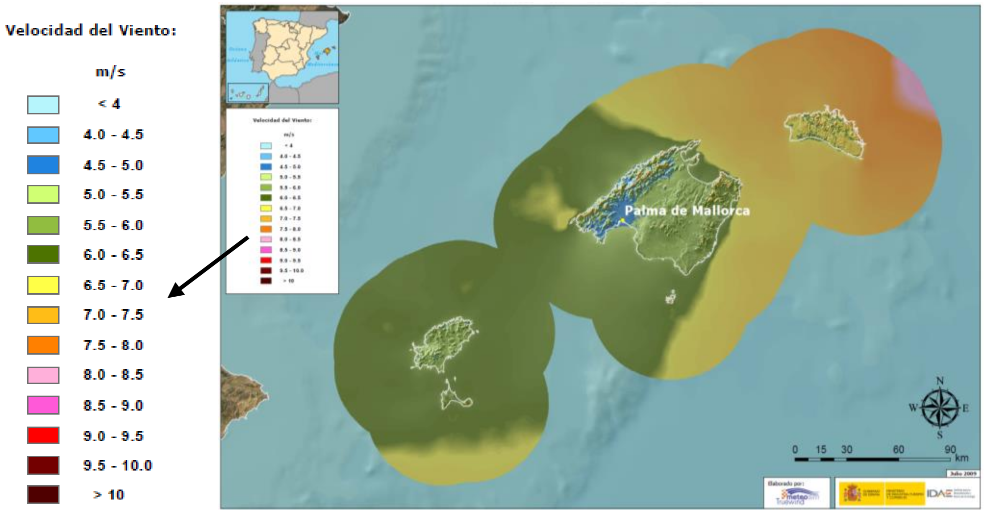

Figure 3.5: Wind map of the Balearic Islands, annual mean speed at 80 m height [17]

Concerning the electric system, wind energy can have a huge penetration but it is an intermittent energy source. It also gives variable power, which is consistent from year to year but varies greatly over shorter time scales. This can affect the stability of the whole system and needs to be controlled. Due to its intermittency, wind power has a good performance in hybrid systems, for example being able to compensate the PV energy gap of winter.

3.4. Other renewable sources

Biomass is a collective term for all plant and animal material. Biomass energy aims to obtain through combustion the solar energy stored in organic matter. It is a renewable fuel as long as it comes from sustainable sources such as forest residues, tree surgery waste, energy crops, agricultural waste, and other wood residues. Besides, the combustion releases CO_2, therefore it can be considered a neutral resource in terms of net emissions only if it is used in the same amount that the net biomass production of the ecosystem that is exploited. The combustion also may be dangerous due to the production of toxic substances [18].

Geothermal energy is the thermal energy generated and stores in the Earth. To generate electricity, it is needed to have high temperature (T > 150 ºC), which are usually located close to tectonically active regions. Earth's temperature rises with depth from the surface to the core, and the locations selected to build a geothermal power station either are on top of an aquifer or inject water in the hot ground. With a turbine, hot water and stream are extracted from the aquifer to generate electricity, then cold water is returned to the aquifer to ensure its sustainability. Geothermal power is considered to be renewable because any projected heat extraction is small compared to the Earth's heat content, but its extraction must still be monitored to avoid local over-cooling [19].

Ocean energy can be obtained from waves, tides, and currents. Wave energy is transformed into electricity by converters; those converters include oscillating water columns that trap air pockets to drive a turbine, oscillating body converters that use wave motion, and overtopping converters that make use of height differences. Tidal energy, produced either by tidal-range technologies using a barrage to harvest power between high and low tide, or by tidal-current or tidal-stream technologies. Salinity gradient energy, like the one that occurs where a river empties into an ocean, may be obtained by “pressure retarded osmosis” and “reverse electrodialysis”. Ocean thermal energy conversion, which generates power from the temperature difference between warm surface seawater and cold seawater at 800 – 1000 meters depth. It is important to mention that ocean energy is still at the research and development stage, and are not yet commercially available [20].

For this project, one main aspect is to choose the energy sources needed. Photovoltaic and wind power are the most popular and the ones that here will be used. All other renewable sources have more complexity to be applied, for that reason, they will not be used in this project.

3.5. Battery

A battery is the main form of energy storage in power systems. The parameters used to describe the characteristics of the battery are the voltage (V), the loading capacity (Ah) and the amount of energy that can supply (W). When the production exceeds the consumption at a determined time, the exceeding energy can be stored in batteries so it can be used later when generation is not enough to supply the demand.

This process of loading and downloading the battery is called a cycle. Battery lifetime can be expressed in years but it is usually related to a number of cycles. At the same time, usually batteries lose capacity over time with each cycle. There are also different types of batteries, which influence their lifetime. According to their use, batteries can be stationary (if the period of time to realize a cycle is at least two seasons) or daily (if the cycles usually last for one or a few days). Depending on the material they are made of, batteries can be made of lead-acid, lithium ion, or hydrogen. Their reduced lifetime and their composition with toxic substances make causes a lot of waste and its treatment is very important, if it is not done correctly there can be a huge negative environmental impact.

In power systems, the most commonly used is the battery storage power station, which is a type of energy storage power station that uses a group of batteries to store electrical energy. In addition to the storage of exceeding energy produced, these batteries can be used also as a tool to enhance power system stability, aid power transfer, improve reliability and power quality. For all those reasons, power systems usually have some storage system implied.

3.6. Hybrid power systems

Hybrid power systems combine two or more modes of electricity generation together, usually using renewable technologies such as solar PV and wind turbines. Hybrid systems provide a high level of energy security through the mix of generation methods, and often will incorporate a storage system (battery) or small fossil fuel generator to ensure maximum supply reliability and security.

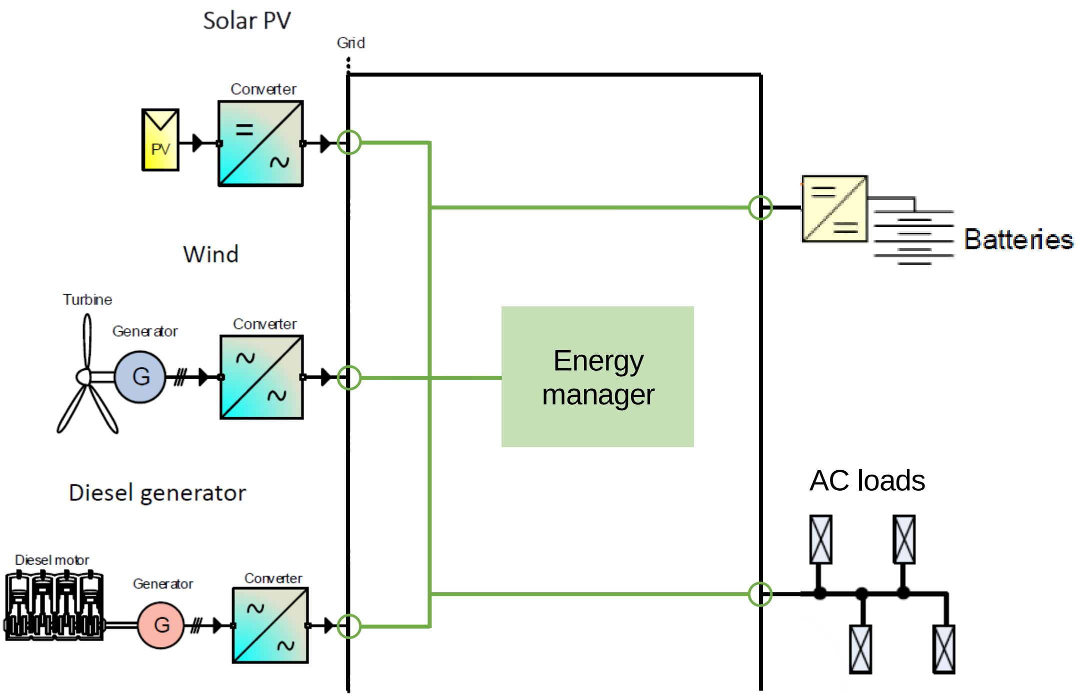

Figure 3.6: Example of a hybrid power system

Specifically, hybrid renewable energy systems are becoming popular as stand-alone power systems for providing electricity in remote areas due to advances in renewable energy technologies and the increasing costs of petroleum products. Islands is one of those places where hybrid power systems have more possibilities of success due to their isolation and the difficulty to transport energy to them.

An example of hybrid power system for islands can be found in Tuvalu, in the South Pacific. Vaitupu (the largest of the nine islands) was powered by diesel since the United Nations started a project of 1 M$. The project ended with a hybrid system with PV power, some batteries and the diesel generator. The system consists of an AC-coupled off-grid system from SMA Technology; equipped with 9 x Sunny Island and 6 x Sunny Mini Central 8000TL based on 3 banks of 4500 Ah FLA batteries each at 48 V from BAE. The PV system consists of 46 kW of solar power mounted on bespoke aluminium football stand in order to provide a secondary use. This new system allowed the community to save up to 65000 $ annually. [21]

First are selected the renewable energy sources, and then the hybrid power system to study is defined. In this thesis, there will be two power systems with the same renewable sources and different non-renewable ones, those systems are:

- PV + wind turbines + storage + fossil fuel generator
- PV + wind turbines + storage + cable with Mallorca and the peninsula

4. Data collection and pre-analysis

4.1. Consumption

The first step of the project is to analyse the demand of the grid, to size correctly the new generation system.

Red Electrica de España (REE) facilitated the electric power consumption every 10 min from Menorca's island in 2019 [22]. Given the big amount of data, it was decided to establish a time reference of 1h for the analysis. So, it was calculated the hourly consumption.

As can be seen in Figure 4.1, hourly consumption oscillates between 30 and 60 MWh in winter. Whereas in summer it almost doubles its value, going from 50 to 110 MWh. To compare both periods, there will be two parallel analyses taking as a representative data one day of March and one day of August. The total amount of electrical energy consumed is around 495 GWh every year.

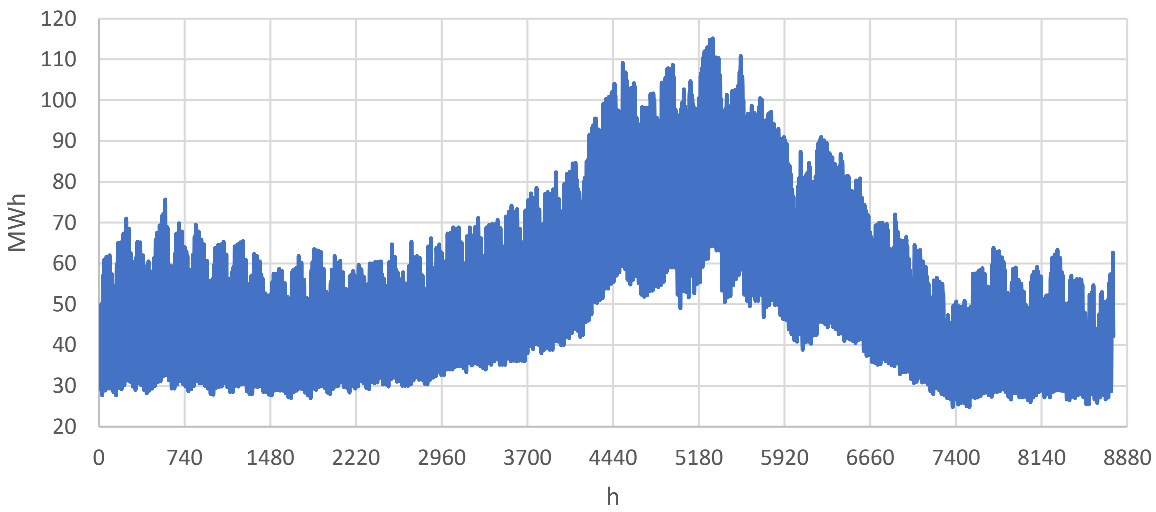

Figure 4.1: Electric power consumption, plot of every hour of the year 2019

Analysing daily consumption, it can be seen a pattern. In Figure 4.2, secondary vertical lines represent week separation and the blue line represents the consumption each day. As a result, in general, there is one day each week whose electric consumption is significantly lower than the rest of the days of that week, typically Sunday.

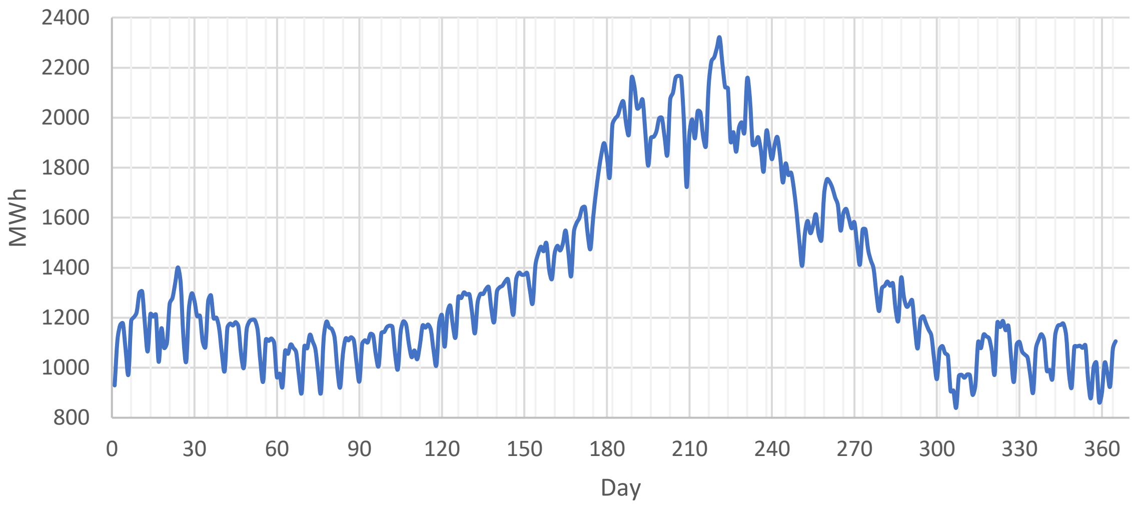

Figure 4.2: Daily consumption of 2019

It also can be seen that each week can form a curve similar to a parabola. In Figure 4.2 it is seen thanks to the distinctive consumption value of each Sunday, but in Figure 4.3 this effect can be seen more in detail in the March consumption (parabola in green). This effect can be easily seen during all year, except for some weeks of August.

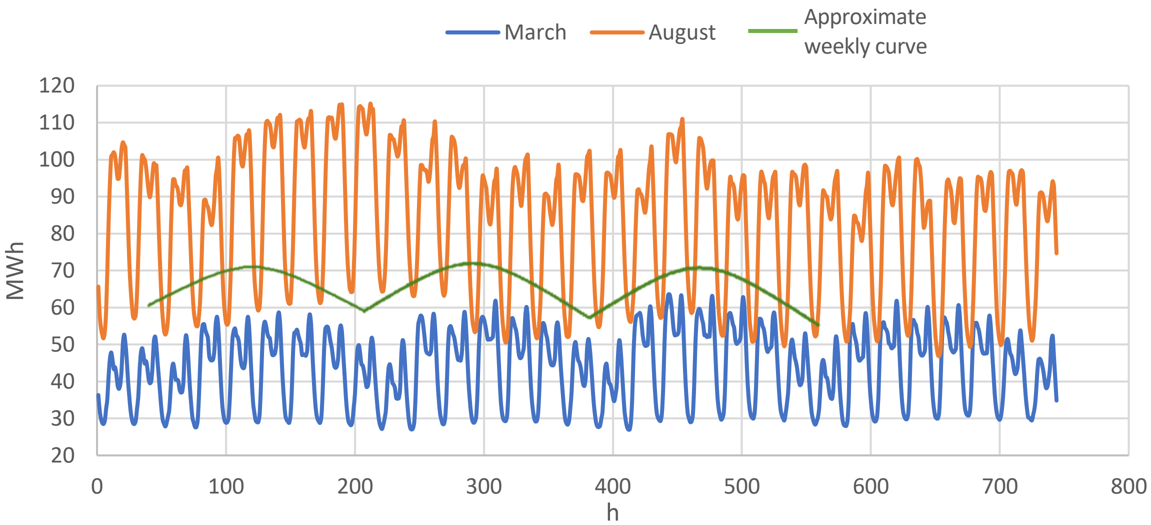

Figure 4.3: Hourly consumption of March and August

Comparing winter and summer, or as a representative, March and August respectively, some observations can be done (Figure 4.3). Apart from the previously mentioned difference in consumption values, there is a great difference of wave amplitude between both months, meaning by wave amplitude the difference between the maximum and minimum daily consumption values. In March, it can be consumed until 60 MWh during the day and around

30 MWh during the night (from 0 to 6 am), making a wave amplitude of 30 MWh at most. While in August, it can be consumed until 110 MWh during the day and between 50 and 60 MWh during the night, making a wave amplitude of around 60 MWh. This makes sense, as doubling each value implies doubling wave amplitude, but it can be interesting to study how this affects the whole system.

In Figure 4.3 it is also clearly seen that hourly consumption of all days follows the same pattern, which can be extrapolated to all days of the year. Every day has two peaks, the first one around 11 am and the second one at 9 pm, usually the second peak is higher than the first one. Between these maximum peaks, there is a minimum point at 5 pm. And at night, the minimum point of all day can be found at 5 am (Figure 4.4).

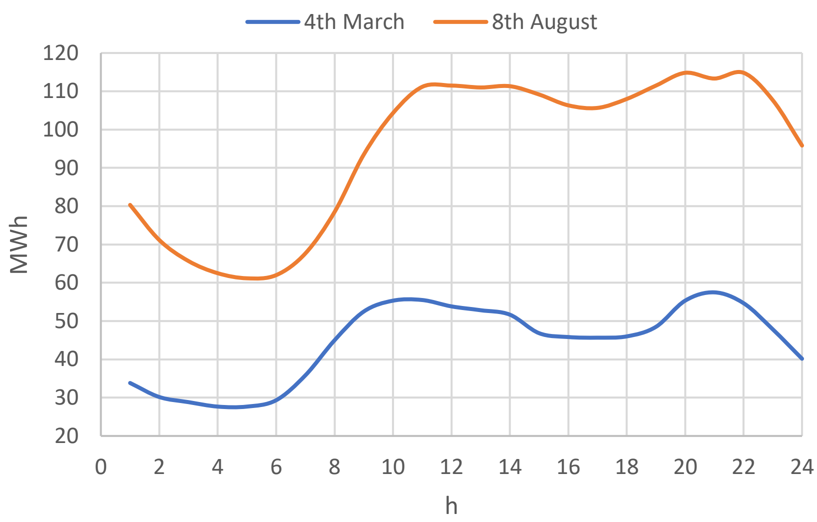

Figure 4.4: Hourly consumption of two representative days

4.2. Photovoltaic capacity

Starting without restrictions regarding the total amount of photovoltaic (PV) panels to install, the important part here is to find and maximize the electricity production by solar power per unity of nominal power installed (in kWp). To do that, the PVGIS system has facilitated the hourly data with the SARAH database of radiation [23].

Menorca is quite big, but to obtain the solar radiation it is needed to select an exact location. That place is Ciutadella, mainly because around it there is a lot of space in good conditions to put solar panels (without shadows). Although at this point of the project it does not seem right to place all photovoltaic production together, but better have distributed production. For that reason, for the analysis, it will be supposed that all Menorca will have the same solar radiation, no matter the exact location of the photovoltaic panels.

There are two main properties of the photovoltaic system: slope and azimuth. Due to the location in the globe, there has been selected an azimuth of 0º (south) to do the analysis, although in practice the solar panels may have a small deviation. The slope is chosen to best adjust the energy production to the consumption seasonally. Here the objective is to maximize production, especially in winter, since anyway summer production doubles (Figure 4.5). Therefore, the slope should be 35º. On the other hand, system losses have been supposed 14% on average, as it is the standard value for losses in cables and dirt in the modules. Given all the previous conditions, the system can generate annually 1526 MWh / kWp installed.

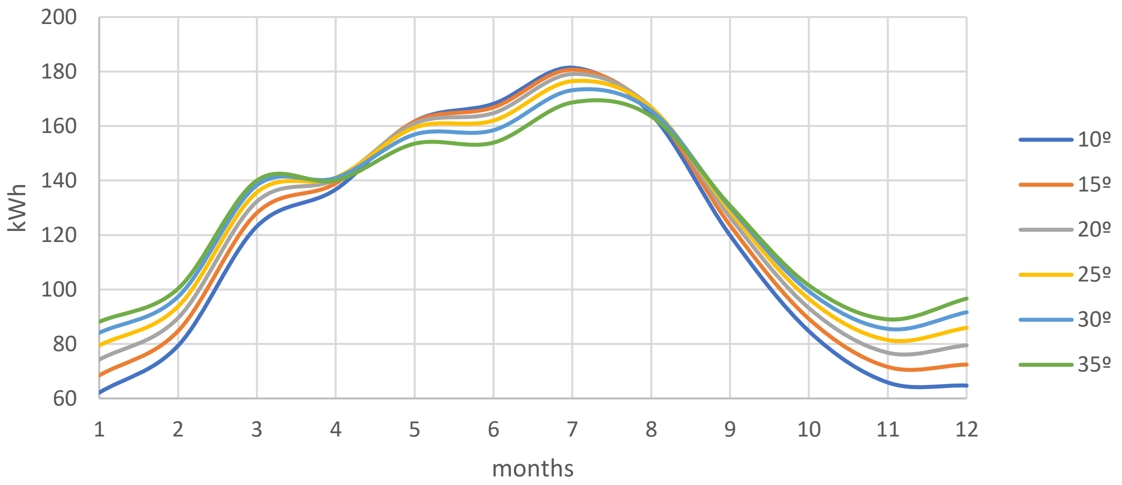

Figure 4.5: Monthly solar production for a nominal power of 1 kWp

A market study will define the exact properties of the modules. To do it, several sources have been consulted [24], [25], [26] to find the PV modules with higher power and efficiency. This research resulted in Table 1. Due to its similarity, the following calculations of the project are valid for both modules.

	Monocrystalline PERC half-cell module (JAM72S10 390-410/PR)	Monocrystalline PERC (ESPSC400M)
Power	400 W	400 W
Efficiency	19.9%	20.17%
Dimensions (m)	2.015 x 0.996 x 0.04	1.979 x 1.002 x 0.04
Cost	195.17 € [27]	154.55 € [28]
Technical sheet	Annex C	Annex D

Table 1: Market study of PV modules

4.3. Wind power capacity

The other main source of energy will be wind. The first step is to study the Weibull distribution, then a wind turbine must be chosen according to the wind class, finally, energy production can be calculated. This analysis has focused on the onshore wind turbines, because they are generally less expensive, but offshore analysis could also be done.

As happened with photovoltaics, a specific area must be chosen to search its wind. Given the amount of data needed and the limited access to it, there were not so many locations to choose. Menorca's Airport in Maó is the place that has the main weather station of all the island, and wind is measured at 10 m height. Mean wind speed every half hour from Menorca's Airport in Maó is obtained from a climate website [29], but to verify its authenticity several other websites were compared [30], [31], [32]. Following the initial criteria of the project, the mean wind speed every hour is calculated to standardize the data. Using Matlab, the program in Annex E is defined to find the Weibull parameters and plot the data (Figure 4.6). In this case, the shape parameter is $k = 1.5372$ and the scale parameter is $c = 4.8587$. Comparing the results with the IEC Wind Class, it corresponds to a low-level wind or class III.

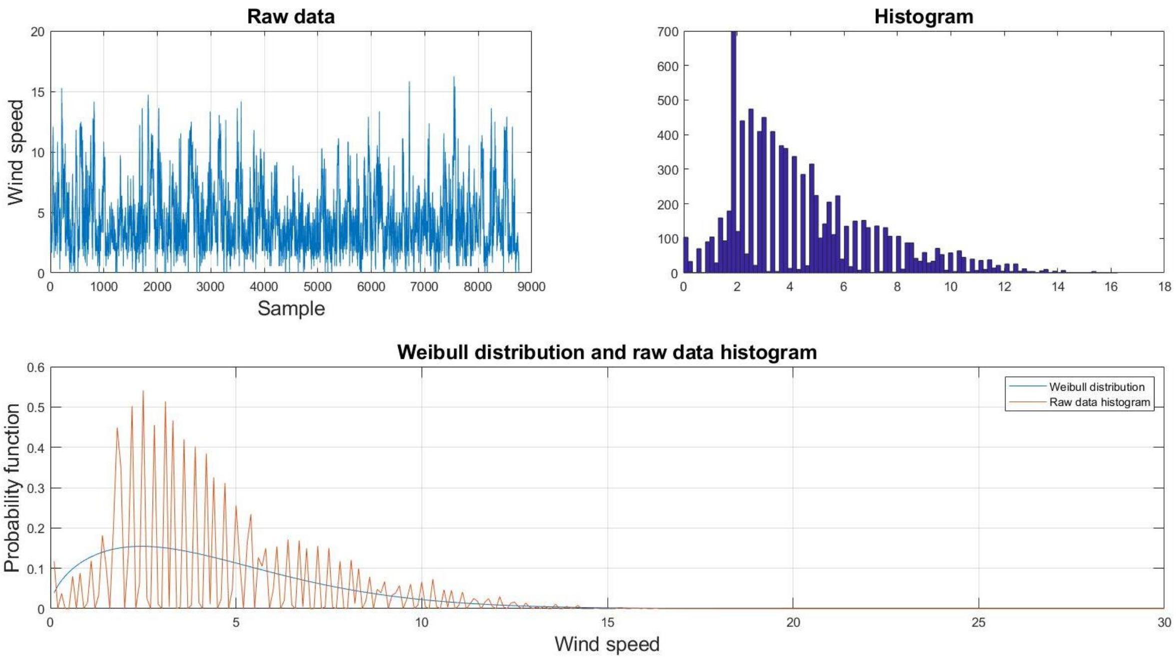

Figure 4.6: Mean wind speed, chronologically

The second step is to do a market study [33], [34] and find the turbine with better performance for low wind speeds. Although low power turbines work quite well in low wind, the focus is put in big turbines that can supply a significant amount of energy with respect to the total consumption. The turbine selected for that purpose is Gamesa 4.5 MW (G128 - 4.5 MW model) [35]. The main characteristics of this turbine are: tower height of 140 m, rotor diameter of 128 m, nominal power of 45000 kW, and the power curve shown in Figure 4.7, other characteristics can be found in Annex F.

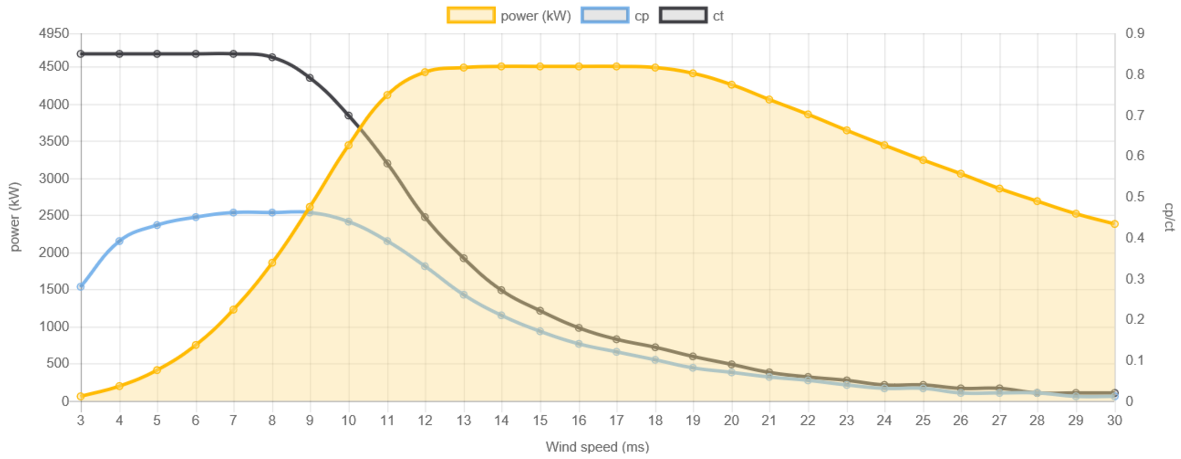

Figure 4.7: Power curve (orange) and power coefficient (blue) of Gamesa 4.5 MW turbine

There are two procedures to obtain the generated power by the turbine: through the power curve, and through the power coefficient (cp). In this analysis, the power curve has been used because with it and the wind speed data you can get the power generation every hour. One aspect to consider is that the equation corresponding to the power curve is not accessible, so it has been approximated by the known points of 3, 4, 5 … 25 m/s and using a linear interpolation between two consecutive points (Figure 4.8).

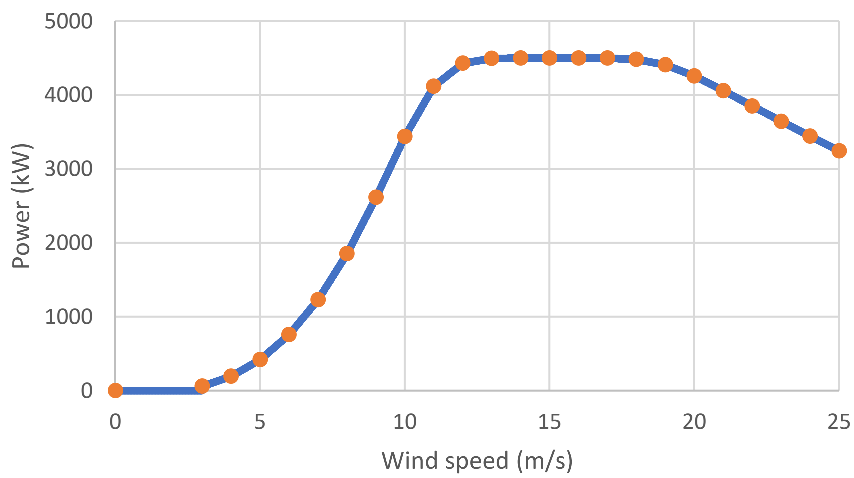

Figure 4.8: Power curve approximation

Now, the wind speed must be corrected to the hub height using (4.1). Where z is the hub elevation, v_{ref} and z_{ref} are the reference speed and elevation (known) respectively, z_0 is the terrain roughness which has been supposed to be 0.2 corresponding to agricultural crops.

$$v = \frac{v_{ref} \ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_{ref}}{z_0}\right)} \tag{4.1}$$

Finally, the power equation is applied to the corrected wind speed to obtain the generation every hour.

5. Economic study of the system components

In this chapter, there are described the current costs of each component, to be able to afterward calculate the total cost of the system. To do it, only the most important parameters are used, which are capital expenditures and operation and maintenance expenditures. Capital expenditures (CapEx) refers to the initial cost of investment. CapEx include the purchase of the land, equipment cost (of the generator and the balance of the system), and financial costs. Operational and maintenance expenditures (OpEx) refers to the ongoing cost for running the system. OpEx include rents, workers' salaries, taxes, insurance, equipment maintenance and repairs costs.

It is also important to know how these costs evolve in time. It allows to validate the accuracy of results and estimate future related projects. Some graphs of costs evolution can be found in Annex G.

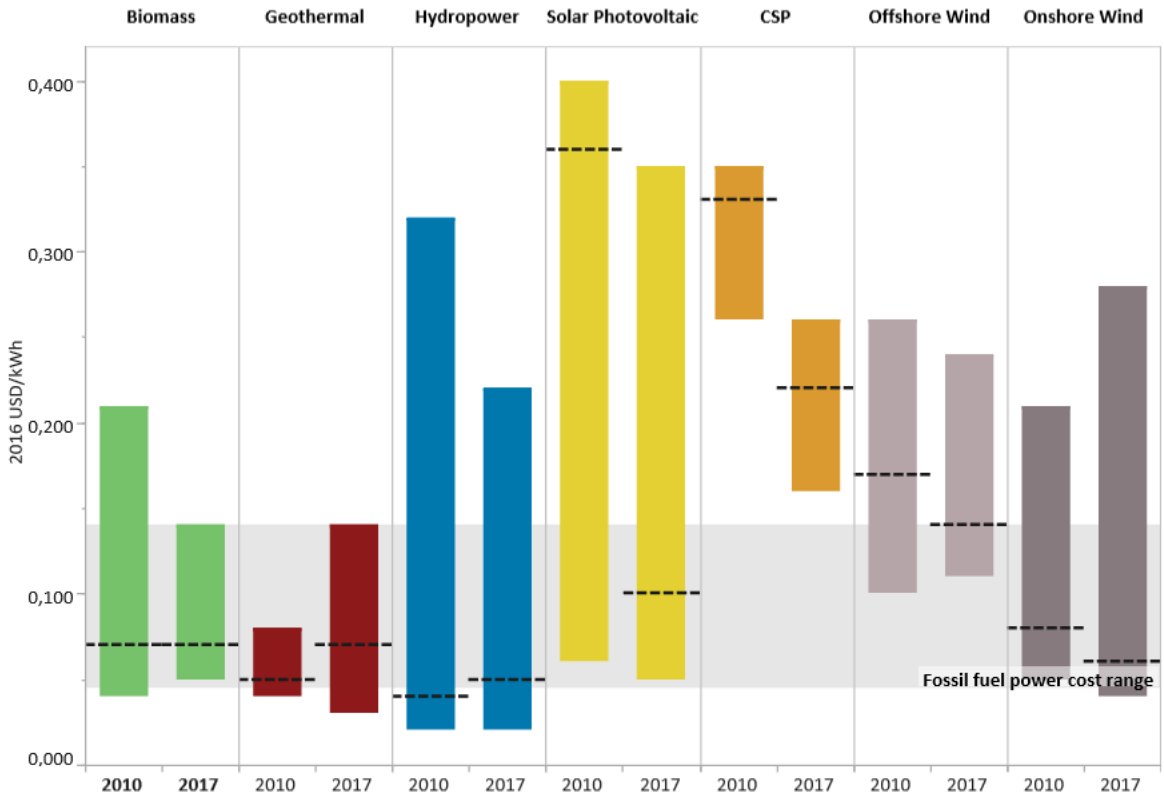

Figure 5.1: Global levelized cost of electricity form utility-scale renewable power generation technologies 2010-2017 [36]

5.1. Photovoltaic system

Costs of the PV system are described as €/kWp installed. Following the objectives of this project, the PV system is considered to be at utility-scale. To find the costs of this system several sources have been consulted, as can be seen in Table 2. The mean cost is the one that will be used afterward.

	[37]	[38]	[39]	[40]	Mean
CapEx	2730	1010	600 - 800	819 - 1001	1337.5
OpEx	39.13	18.2	15 - 20	8.19 - 10.92	21

Table 2: CapEx and OpEx for the PV system in €/kWp installed

Equivalently, those costs can be described in relation to the number of PV modules. Here, it is important to highlight that CapEx is higher than the cost of a PV module found, due to the balance of the system; for that reason, the previously price cannot be used in total cost calculations.

$$CapEx = 1337.5 \frac{€}{\text{kW}} \cdot \frac{0.4\ \text{kW}}{1\ \text{PV module}} = 537 \frac{€}{\text{PV module}} \qquad (5.1)$$

$$OpEx = 21 \frac{€}{\text{kW}} \cdot \frac{0.4\ \text{kW}}{1\ \text{PV module}} = 8.4 \frac{€}{\text{PV module}} \qquad (5.2)$$

PV costs have reduced a lot in the past years, although future prospects only expect a 45 – 70 % of LCOE (levelized cost of energy) reduction in 2050 with respect to the current cost [36], [38], [41]. More detailed CapEx and OpEx evolution can be found in Annex G.

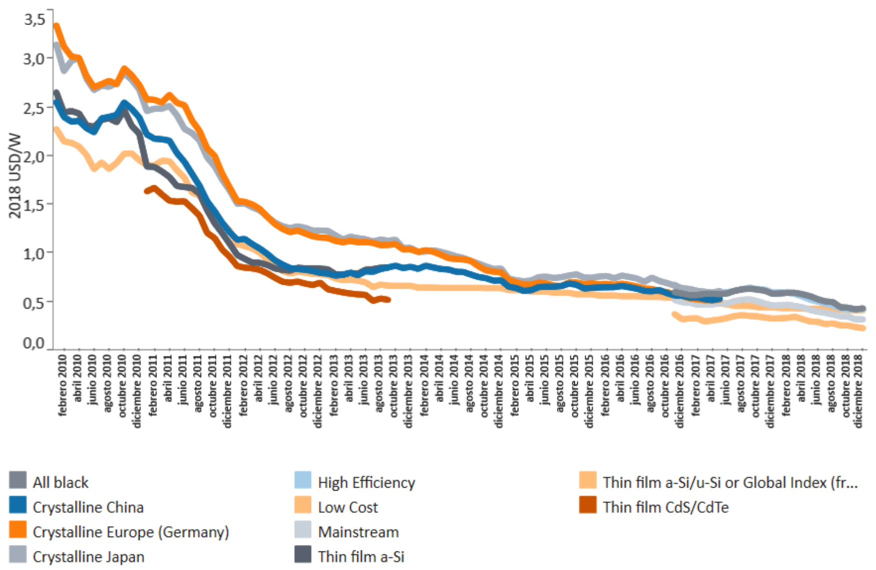

Figure 5.2: Solar PV module costs 2010-2018 [36]

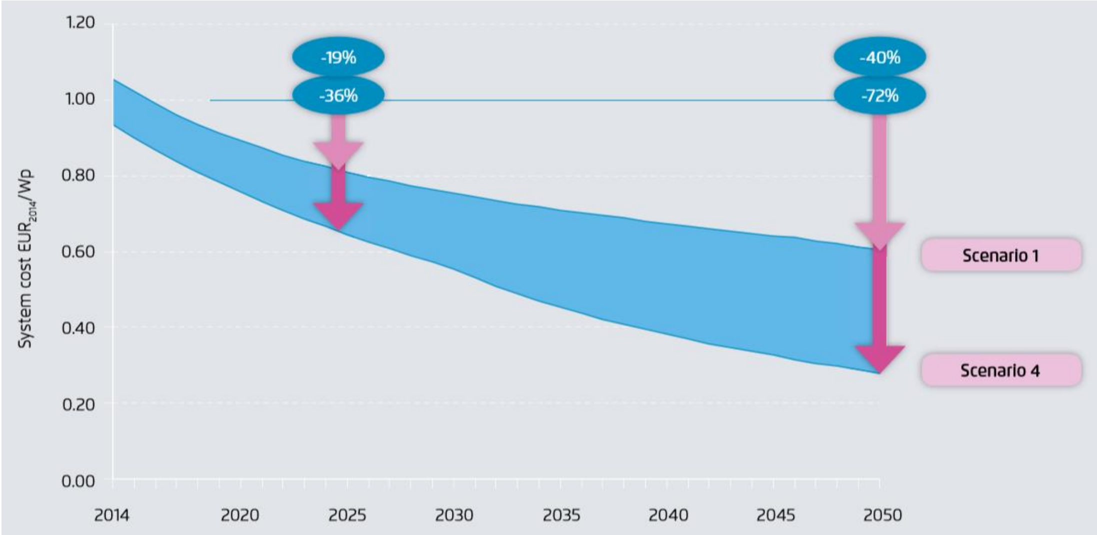

Figure 5.3: Range of future cost developments in different scenarios for utility-scale PV systems [41]

5.2. Wind power system

Costs of the onshore wind power system are described as €/kW installed. To find them several sources have been consulted, as can be seen in Table 3. The mean cost is the one that will be used later.

	[37]	[39]	[40]	[42]	[43]	[44]	Mean
CapEx	1638	1500 - 2000	1001 - 1365	1465.1	1337.7	1200.29	1429
OpEx	71.89	30	25.48 - 33.22	40	40	23.86	39.18

Table 3: CapEx and OpEx for the wind power system in €/kW installed

Equivalently, those costs can be described in relation to the number of wind turbines.

$$CapEx = 1429 \frac{€}{\mathrm{kW}} \cdot \frac{4500\ \mathrm{kW}}{1\ \mathrm{turbine}} = 6430500 \frac{€}{\mathrm{turbine}} \tag{5.3}$$

$$OpEx = 39.18 \frac{€}{\mathrm{kW}} \cdot \frac{4500\ \mathrm{kW}}{1\ \mathrm{turbine}} = 176310 \frac{€}{\mathrm{turbine}} \tag{5.4}$$

Wind power costs have been progressively reduced in the past years, and future prospects expect that this tendency continues, meaning a LCOE reduction of 15 – 30 % in 2050 with respect to the current cost [36], [38].

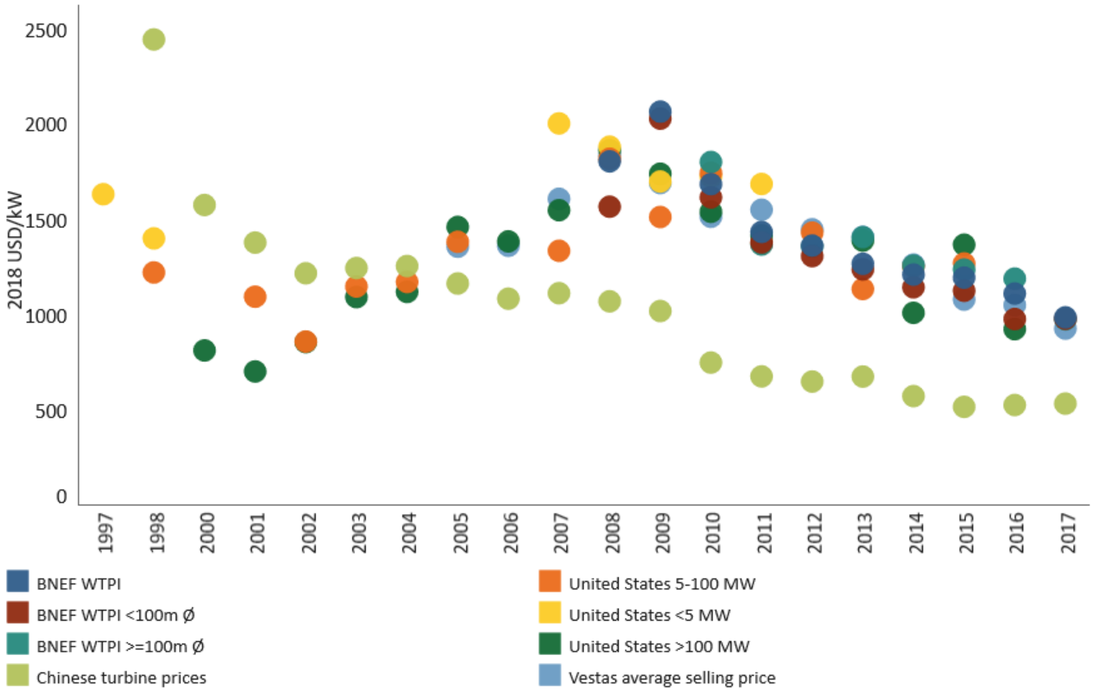

Figure 5.4: Wind turbine costs 1997-2017 [36]

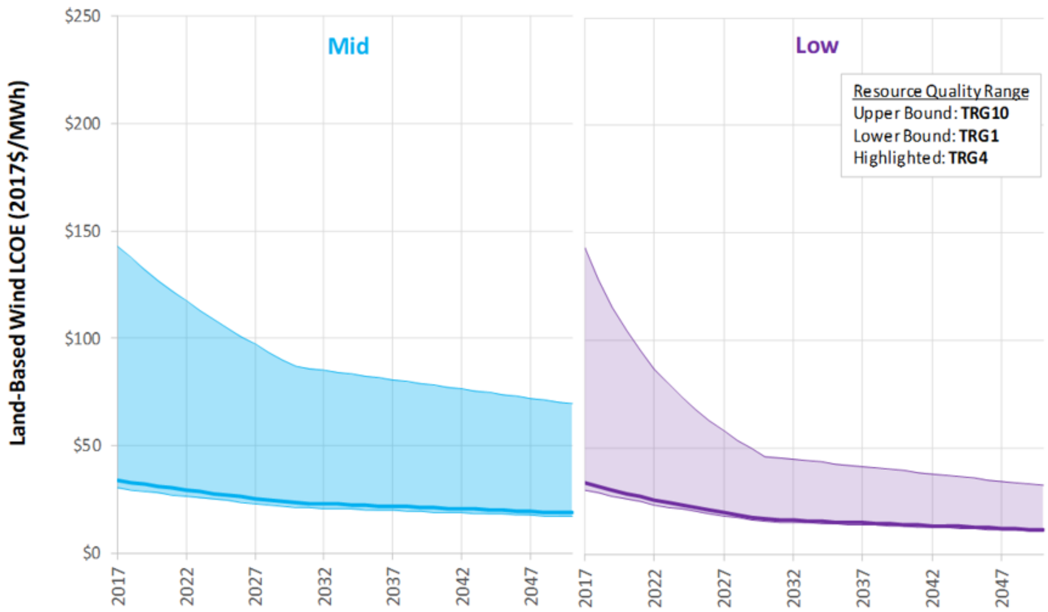

Figure 5.5: Onshore wind LCOE future projections [38]

5.3. Storage system, battery

Costs of the storage system are described as €/kWh installed. To find them several sources have been consulted, as can be seen in Table 4. The mean cost is the one that will be used later, it is calculated for 4h battery because they are the less expensive type.

	[38][1]	[45]	[46]	Mean
CapEx	For 4h: 363.64 For 2h: 518.94 For 1h: 829.545	For 4h: 204.75 - 426.79 For 2h: 222.04 - 445.9 For 1h: 254.8 - 466.83	For Li-ion (LFP and NMC): min = 403.13 mean = 494.13 max = 511.42	For 4h: 391.18
OpEx	2.5% of the capital costs		Li-ion Large scale (>1MW): 9.1	9.1

Table 4: CapEx and OpEx for the storage system in €/kWh installed

Storage system costs have been progressively reduced in the past years, and future prospects expect that this tendency continues, meaning a LCOS (levelized cost of storage) reduction of 31 - 80 % in 2050 with respect to the current cost [38], [45], [47].

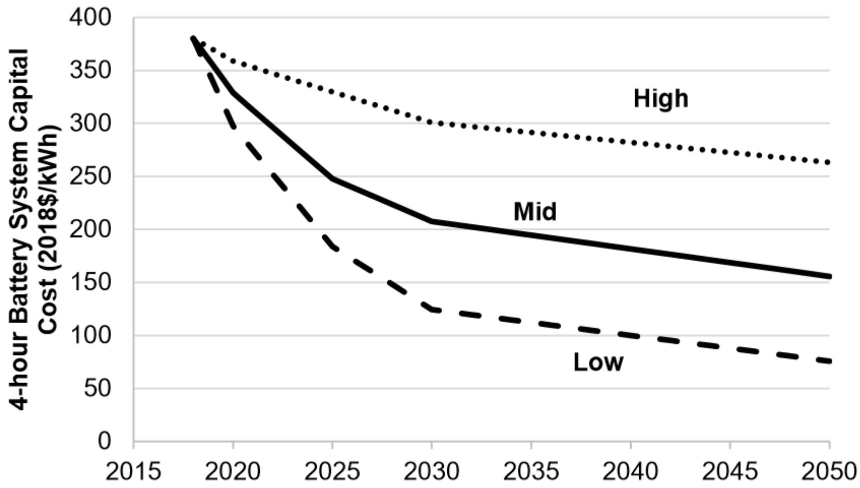

Figure 5.6: Battery cost projections for 4-hour Li-ion systems [47]

[1] Total System Cost ($/kW) = Battery Pack Cost ($/kWh) × Storage Duration (hr) + BOS Cost ($/kW) = = (209 $/kW (Figure A.13) × Storage Duration (hr) + 683 $/kW) · 0.91 €/$

Total System Cost ($/kWh) = Total System Cost ($/kW) / Storage Duration (hr)

5.4. Fuel (diesel)

Costs of the fuel are described as €/kW needed. To find them several sources have been consulted, as can be seen in Table 5. The mean cost is the one that will be used later.

	[37]	[48]	Mean
CapEx	910 - 1183	455 - 728	819
OpEx	36.4 - 47.32	13.65	27.755
Fuel price €/kWh	0.273 - 0.455	0.2617	0.313

Table 5: CapEx and OpEx for the diesel power system in €/kW installed

Diesel power costs have been increasing in the past years, around 0.03 €/kWh more each year, and future prospects expect that this tendency continues [49]. In addition, to facilitate the penetration of renewable sources, governments have been increasing the taxes for releasing CO_2, which specially affects the power plants with non-renewable energy sources.

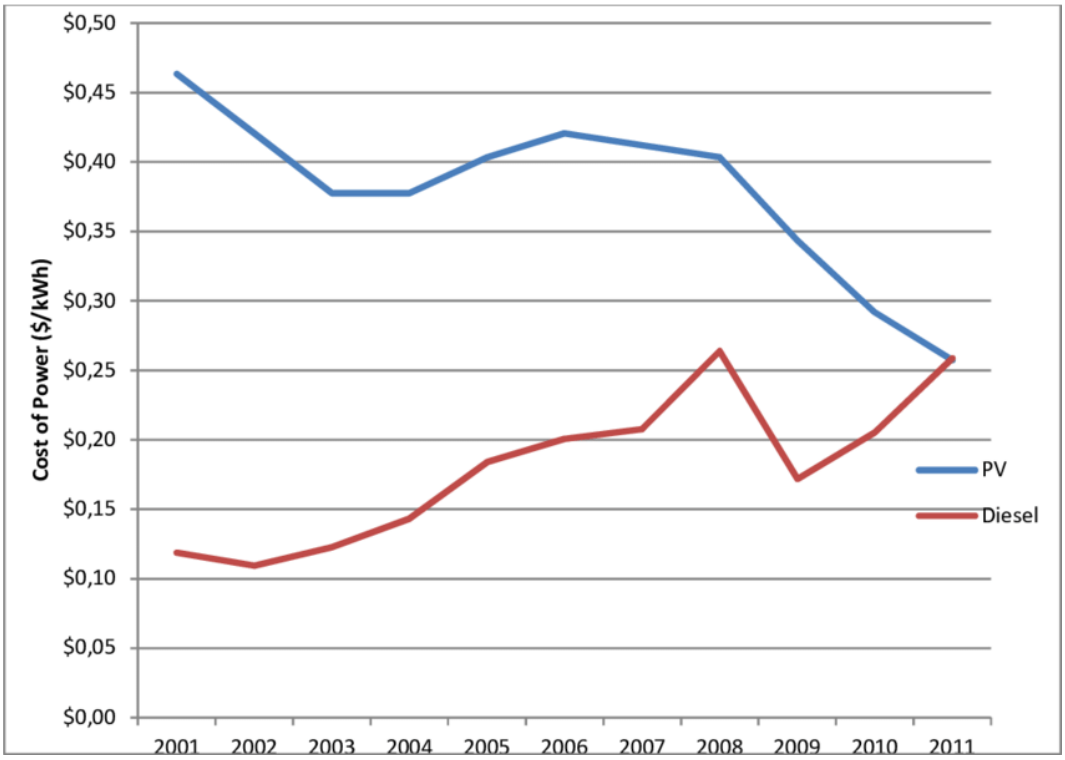

Figure 5.7: Diesel and PV historical evolution of costs [49]

5.5. Cable Mallorca-Menorca

The current cable that connects Menorca to Mallorca supplies electricity from the peninsula. The government has already planned to put several cables that supply a part of the energy consumption. As, according to them, those the cost to generate electricity on the peninsula and transport it are much cheaper than generating it on the Balearic Islands [50].

For the last cable built, and the only one that will be operational soon, Red Electrica has invested initially 84 million € [51], which can be considered the CapEx. This cable has a maximum capacity of 100 MW, but will operate at 30 MW to meet the security criteria. Regarding the OpEx, the cable has some direct annual maintenance cost and some indirect costs which include security and cleaning. According to other undersea cables, the typical approach is to establish a ratio between capital costs and operational expenditure; so for this Mallorca – Menorca cable the OpEx is considered to be 4.3% of the CapEx [52].

Since it can be interesting to later study situations with several cables, the previous costs are expressed in relation to the total power supplied by them.

$$CapEx = \frac{84000000\text{ €}}{30\text{ MW}} = 2800000\frac{\text{€}}{\text{MW}} \tag{5.5}$$

$$OpEx = CapEx \cdot \frac{4.3}{100} = 120400\frac{\text{€}}{\text{MW}} \tag{5.6}$$

These are the costs of transporting the electricity to Menorca, but it needs to be added the actual cost of generation. For that purpose, there is establish an energy cost expressed as €/MWh supplied by the cable. Since the energy comes from the peninsula, and the average price of demand is more or less the same for all of Spain, the cost of generation is supposed to be similar as the average price of demand [9] which is:

$$E = 45\frac{\text{€}}{\text{MWh}} \tag{5.7}$$

The evolution of cable costs will be mainly due to the changes in the cost of the energy that comes from the peninsula. This cost is highly variable over time, but with an annual mean from the last 10 years it can be found that each year it is reduced 0.5022 €/MWh (Figure 5.8)

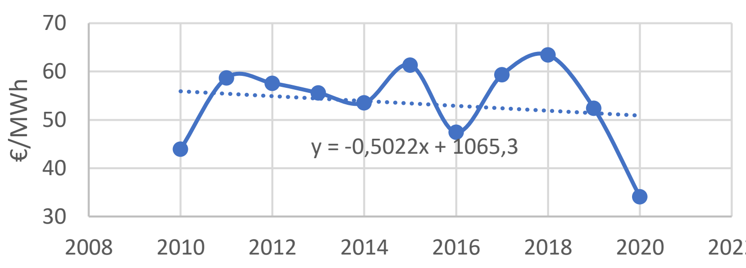

Figure 5.8: Energy generation costs evolution in the peninsula from 2010 to 2020 [10]

6. Design and simulation of the system

6.1. Energetic approach

The variables of the global system are the number of photovoltaic modules, the number of wind turbines, and the total capacity of the batteries. In order to simulate the system in a certain situation, these variables should be taken as given parameters to obtain the state of the system. The simulation has been done using Matlab, where several programs were defined to know different state parameters of the system.

The first approach of the system is to know the amount of renewable energy supplied every hour with respect to the amount of energy consumed, or equivalently the amount of energy not supplied by renewable sources. The initial data is energy consumption, photovoltaic energy generation for each kWp installed, and wind energy generation for each turbine; all this data is stored in vectors where each row corresponds to one hour of the year. The program requires to enter a specific configuration of the system defined by the number of PV modules and the number of wind turbines. The detailed program is shown in Annex H and the main equation is:

$$Ns = D - PV - W \qquad (6.1)$$

Where:

- Ns is the energy not-supplied by renewable sources at every hour
- D is the demand or consumption of energy at every hour
- PV is the total energy supplied by the installed PV power at every hour
- W is the total energy supplied by the installed wind power at every hour

One remarkable aspect of this program is that when the generation exceeds the consumption it returns a negative number. In practice this does not have any sense, but it will be needed afterwards in other programs.

The second approach is similar to the first one but adding the battery. To make this program easier, it is based on the results obtained in the previous program. The battery stores the energy excedents of renewable generation to distribute it later when it is not enough. The variables of this program are the number of PV modules, the number of wind turbines and the total capacity of the battery in MWh. The analysis of the state of the battery is done for every hour of the year. In this case, when the generation exceeds the consumption and it can not be stored, it is considered non-useful energy. This program returns the amount of energy that renewables do not supply (or what is the same, the non-renewable energy required) for every hour, and the annual excess of renewable energy production. The detailed program is shown in Annex I.

The consumption not supplied by renewable sources must be supplied by other sources such as fuel or the cable with Mallorca. This may lead to different analysis, but energetically speaking, they are only used to fill the gap between renewable generation and consumption.

Auxiliary programs have been also useful to visualize the results. For example, in Annex J, the program returns the annual consumption, the amount of non-renewable energy required, the amount of renewable energy consumed and its percentage with respect to total consumption, and the exceeding energy that will not be used. For example, in a system with 500000 PV modules (200 MWp), 30 wind turbines (135 MW) and 360 MWh of battery capacity; renewable sources will produce annually 432.02 GWh, which represents 87.44% of the consumption, and there will be 311.06 GWh of excess of energy (not used) annually, non-renewable sources should provide 62.03 GWh annually and a power of 110.15 MW.

6.2. Economic approach

The main objective of the economic approach is to know the cost per unit of energy. To do that, there will be studied three cases depending on the energy sources considered: only renewable, renewable + fuel, renewable + cable with Mallorca. The cost function used in this project is inspired in LCOE.

The levelized cost of energy (LCOE) is a measure of the average net present cost of electricity generation for a generating plant over its lifetime [53]. It is calculated as the sum of costs over lifetime divided by the sum of electrical energy produced over lifetime:

$$LCOE = \frac{\sum_{t=1}^{N} \frac{CapEx_t + OpEx_t + F_t}{(1-r)^t}}{\sum_{t=1}^{N} \frac{E_t}{(1-r)^t}} \tag{6.2}$$

Where:

- $CapEx_t$ is the capital expenditures (€) of the generator and the balance of the system in the year t
- $OpEx_t$ is the operational and maintenance expenditures (€) in the year t
- F_t is the fuel expenditures in the year t
- E_t is the electrical energy generated in the year t
- r is the discount rate
- N is the expected economic lifetime of the power plant

To simplify the (6.2), r is supposed to be 0 and the operational and fuel expenditures are supposed to be the same all the years. With that, instead of calculating the LCOE for the system lifetime, it can be calculated as the mean for a single year. Therefore, (6.2) can be wrote as:

$$LCOE \approx \frac{\frac{CapEx_{total}}{N} + OpEx_t + F_t}{E_t} \tag{6.3}$$

The system of study has two main characteristics that differ from the LCOE assumptions. It includes batteries, for that reason LCOE should be modified for storage systems, which means that instead of generated energy it should use delivered energy. In addition to the storage, the study system has several sources, so LCOE must include the costs of all sources. Applying all these changes, it is obtained a new study parameter called $LCOE_m$.

The last consideration mentioned may sound simple but the N parameter is difficult to determine for the whole system, since each source has different lifetime expectation. In general, life expectancy is 20-25 years for PV systems, 20-25 years for wind turbines [54], 20-30 years for fuel generators, 5-15 years for batteries, and 40-50 years for undersea cables [55]. To make it easier, there will be considered a mean lifetime of 20 years for all technologies. And to compensate the reduced lifetime of the batteries, their operational expenditures is considered to be the one described in Chapter 5.3 multiplied by 3.7. The same way, the capital expenditures of the cable with Mallorca will be only half of that described in Chapter 5.5. Numerical justification of these changes can be found in Annex K.

The variables in the calculation of $LCOE_m$ are the number of PV modules, the number of wind turbines and the total capacity of the battery in MWh. The cost parameters needed can be calculated from the economic study of each device and its amount, obtaining the following equations:

$$C_{PV} = 537 \cdot n_{PV} \tag{6.4}$$

$$C_w = 6430500 \cdot n_w \tag{6.5}$$

$$C_{bat} = 391180 \cdot E_{bat} \tag{6.6}$$

$$C_F = 819000 \cdot P_{nr} \tag{6.7}$$

$$C_{cable} = 1400000 \cdot P_{nr} \tag{6.8}$$

$$Op_{PV} = 8.4 \cdot n_{PV} \tag{6.9}$$

$$Op_w = 176310 \cdot n_w \tag{6.10}$$

$$Op_{bat} = 33670 \cdot E_{bat} \quad (6.11)$$

$$Op_F = 27755 \cdot P_{nr} \quad (6.12)$$

$$Op_{cab} = 120400 \cdot P_{nr} \quad (6.13)$$

$$F = 313 \cdot E_{nr} \quad (6.14)$$

$$E = 45 \cdot E_{nr} \quad (6.15)$$

Where:

- C_{PV} is the capital expenditures for PV power
- C_w is the capital expenditures for wind power
- C_{bat} is the capital expenditures for the batteries
- C_F is the capital expenditures for fuel power
- C_{cab} is the capital expenditures for the cable with Mallorca
- Op_{PV} is the operational and maintenance expenditures for PV power
- Op_w is the operational and maintenance expenditures for wind power
- Op_{bat} is the operational and maintenance expenditures for the batteries
- Op_F is the operational and maintenance expenditures for fuel power
- Op_{cab} is the operational and maintenance expenditures for the cable with Mallorca
- F is the fuel cost (diesel)
- E is of the energy that comes from the cable
- n_{PV} is the number of PV modules
- n_w is the number of wind turbines
- E_{bat} is the total installed capacity of the batteries in MWh
- P_{nr} is the power (MW) necessary from fuel or the cable to supply all remaining demand
- E_{nr} is the energy necessary from fuel or the cable to supply all remaining demand

It is important to mention that, it is considered that there will be built a new fuel power plant. This supposition puts the fuel power at the same level as the other sources that have CapEx. Although there is already a thermal power plant that uses fuel-oil and gas-oil, it pollutes a lot and is currently in a process of renovation to reduce its emissions; so either way there will be an important investment.

Another consideration is that the cable costs are in function of the total power needed from the cable, this means that in practice there may be several cables and each one contributes with less power. This analysis allows to easily evaluate various situations without restrictions on the number of cables.

For the case that only considers the renewable sources, there will be obtained a partial $\mathrm{LCOE_m}$, since in general renewable sources will not supply all consumed energy. It is calculated using (6.16), where $\mathrm{E_r}$ is the amount of renewable energy consumed in MWh.

$$LCOE_m = \frac{\frac{C_{PV} + C_w + C_{bat}}{N} + Op_{PV} + Op_w + Op_{bat}}{E_r} \qquad (6.16)$$

For the case of renewables and fuel, $LCOE_m$ is calculated using (6.17), where D is the annual consumption in MWh.

$$LCOE_m = \frac{\frac{C_{PV} + C_w + C_{bat} + C_F}{N} + Op_{PV} + Op_w + Op_{bat} + Op_F + F}{D} \qquad (6.17)$$

And for the case of renewables and the cable with Mallorca, $LCOE_m$ is calculated using (6.18), where D is the annual consumption in MWh.

$$LCOE_m = \frac{\frac{C_{PV} + C_w + C_{bat} + C_{cab}}{N} + Op_{PV} + Op_w + Op_{bat} + Op_{cab} + E}{D} \qquad (6.18)$$

The programs used for each case can be found in Annex L, and they follow the structure shown in Figure 6.1.

- Number of PV modules
- Number of wind turbines
- Battery capacity in MWh

- Energetic variables (P_{nr} and E_{nr}) taken from the energetic analysis (Annex J)
- Calculation of costs using (6.4 - (6.15

- $LCOE_m$ calculated using (6.16 - (6.18 according to the case

Figure 6.1: Scheme of how the programs in ANNEX work

7. Optimization

7.1. Method

The objective of this chapter is to find the best configuration of the system. The variables to find are the number of PV modules, the number of wind turbines and the total capacity of the battery in MWh. And the indicators on which the result will be based are the percentage of renewable energy consumed and the $LCOE_m$, both indicators are defined in previous chapter.

The optimum configuration of the system is the one that minimizes the $LCOE_m$ and maximizes the use of renewable energy.

Due to the complexity of the system, it is very difficult to build a mathematical model to which optimization algorithms can be applied. Instead of this, the procedure to find that optimum is:

1. Simulate some configurations and find the value of the indicators at each configuration, since at this point it is an straightforward task.
2. Compare the results and optimize the value of a new indicator

The new indicator, defined in this procedure as the objective function, can be described as the ratio (7.1) which should be minimized.

$$R = \frac{LCOE_m}{\%\, E_r} \tag{7.1}$$

At this point, a new restriction is defined in order to not oversize the system. To do that the parameter to focus is the exceeding energy, returned from the energetic analysis. This parameter shows the energy produced annually by renewable sources that is not consumed in that moment and can not be stored in the battery, apparently this energy is “thrown away” and does not generate any profit (neither economic or energetic). For that reason, the exceeding energy should be minimized; but taking into account that there will be always an excess because the batteries are quite expensive and even if the objective was to fix the excess at 0 MWh, the battery capacity would be oversized. To find a balance point between oversizing the generation and the storage, the inflection point has been fixed at an excess equal to the annual consumption of Menorca. This way, all configurations with an excess above 295 GWh will be automatically deleted from the set of possible optimum configurations; or what is the same, the optimum configuration can generate at most 200 % of the electric demand. A consideration not taken into account here is that the exceeding energy could be sold or injected to the grid.

This optimization procedure requires a lot of intermediate calculations. To simulate some configurations, a 3D mesh of the variables is defined. And to not collapse the computer system, several iterations should be done by decreasing the total size of the mesh and increasing its quality. Consequently, the procedure requires a considerable amount of time, due to the big amount of data to process. An example of program used can be found in Annex M.

As explained before, there will be studied three cases depending on the energy sources considered: only renewable, renewable + fuel, renewable + cable with Mallorca.

7.2. Results

7.2.1. Only renewable sources

This case is not the final objective of the study, but it shows some important information. An important consideration of this case is that only renewable sources provide energy, no fuel or external support by cable are considered. That way, $LCOE_m$ is only partial, since it calculates the cost of energy but the amount of energy produced is variable and does not supply all the demand. Although the $LCOE_m$ is relative to all system components, the % of renewable energy for a determined system configuration (number of PV modules, number of wind turbines and battery capacity) will be the same in all cases (Figure 7.1); the excess of energy (energy produced that will not be used) will also be the same in all cases for the same configuration (Figure 7.2).

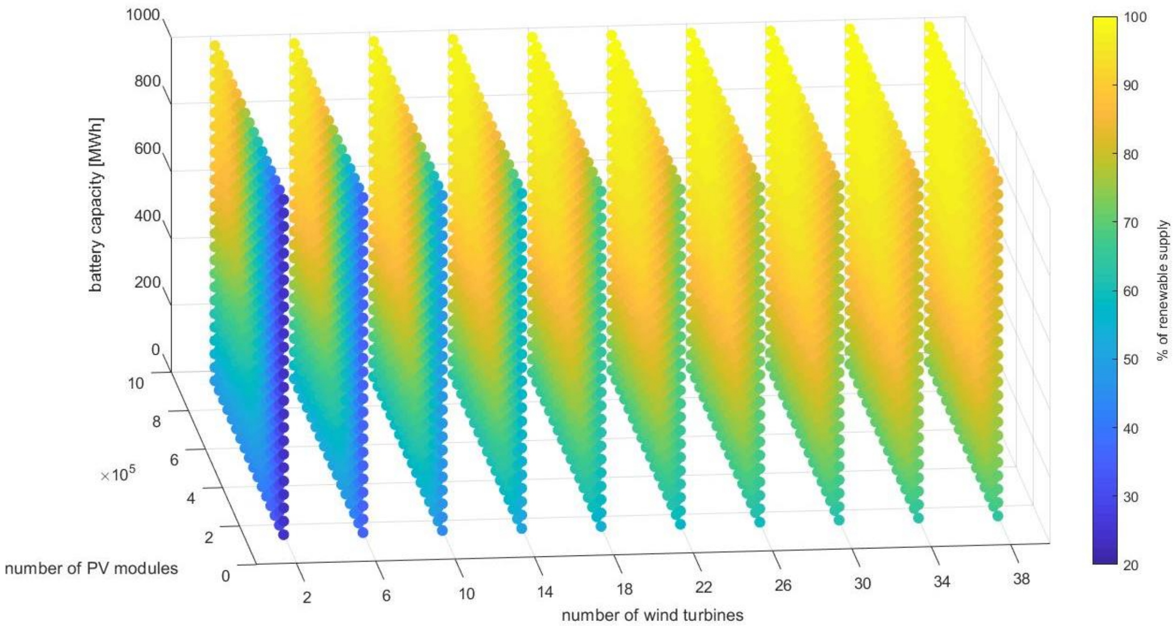

Figure 7.1: % of renewable energy consumed (colormap) in function of the system configuration (number of PV modules, number of wind turbines and battery capacity)

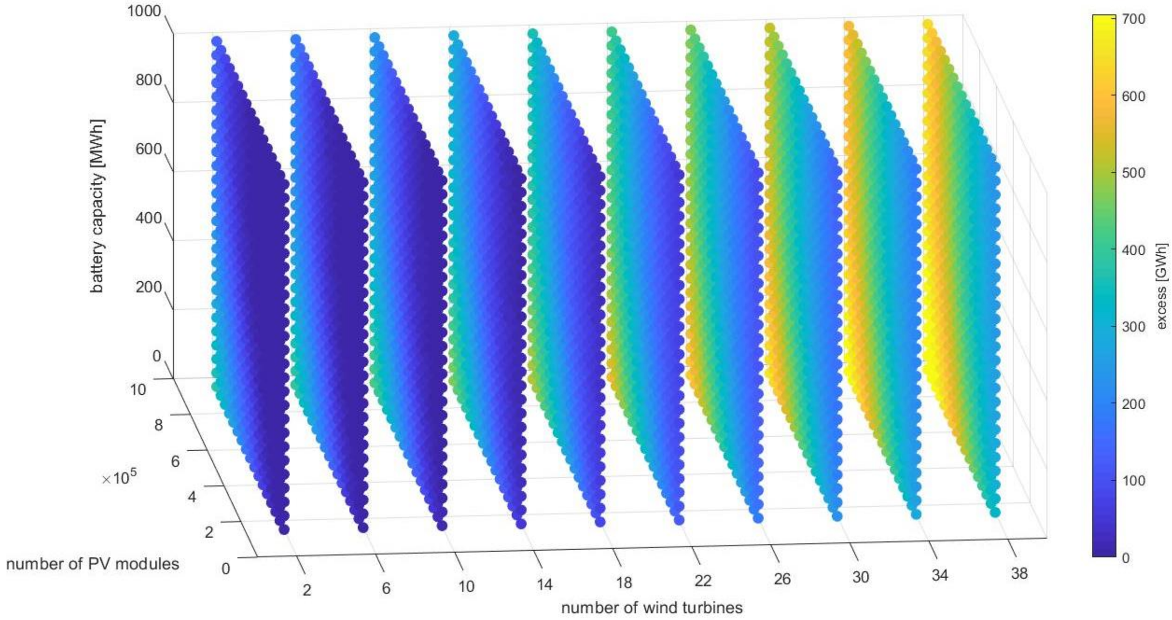

Figure 7.2: Amount of exceeding energy (colormap) in function of the system configuration (number of PV modules, number of wind turbines and battery capacity)

There can be made two type of graphics: the ones that relate the variables with the results (Figure 7.3), and the ones that relate the results between them (Figure 7.4). Each graph type can be used to obtain different information and some of them may be used to complement each other.

For example, to study the properties of a certain configuration, in Figure 7.1, Figure 7.2 and Figure 7.3 selecting a point by the axes, the colormap indicates the % of renewables, the excess and the $LCOE_m$ respectively. Whereas in Figure 7.4 it is impossible to determine the system configuration, but it can be seen how the properties interact with each other, and so it is easier to find characteristic points, for example the ones that define the upper-left limit of the profile. It is also possible to go from a characteristic point in Figure 7.4 to a system configuration, but it will require to cross de data from all four figures, which can be difficult.

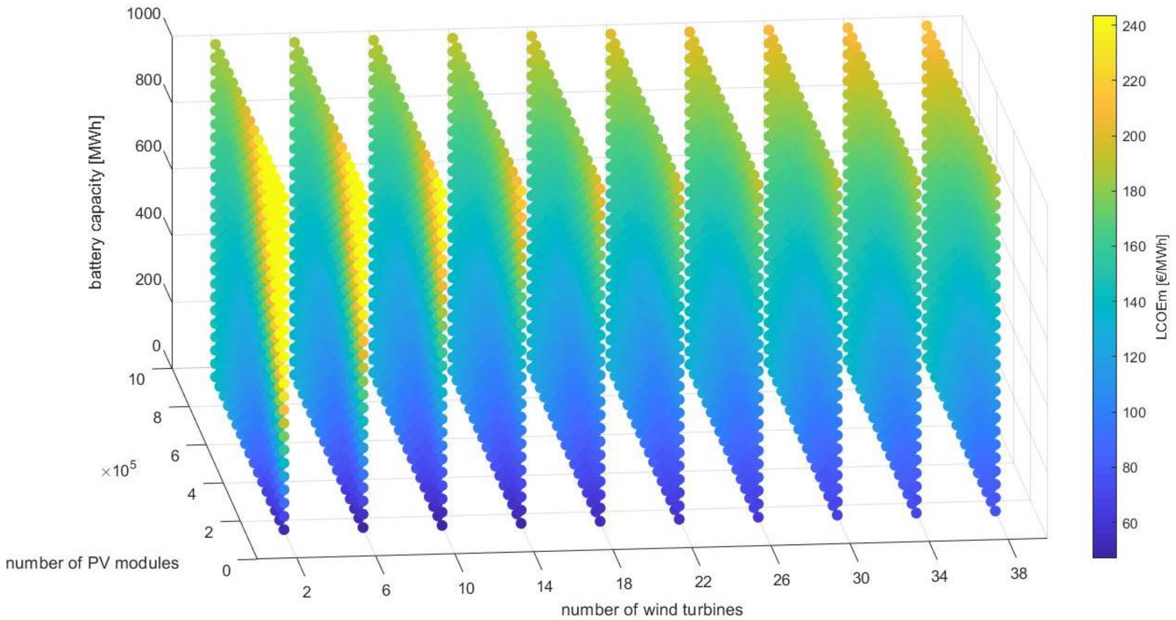

Figure 7.3: $LCOE_m$ in €/MWh *(colormap) in function of the system configuration (number of PV modules, number of wind turbines and battery capacity) for the case of only renewables*

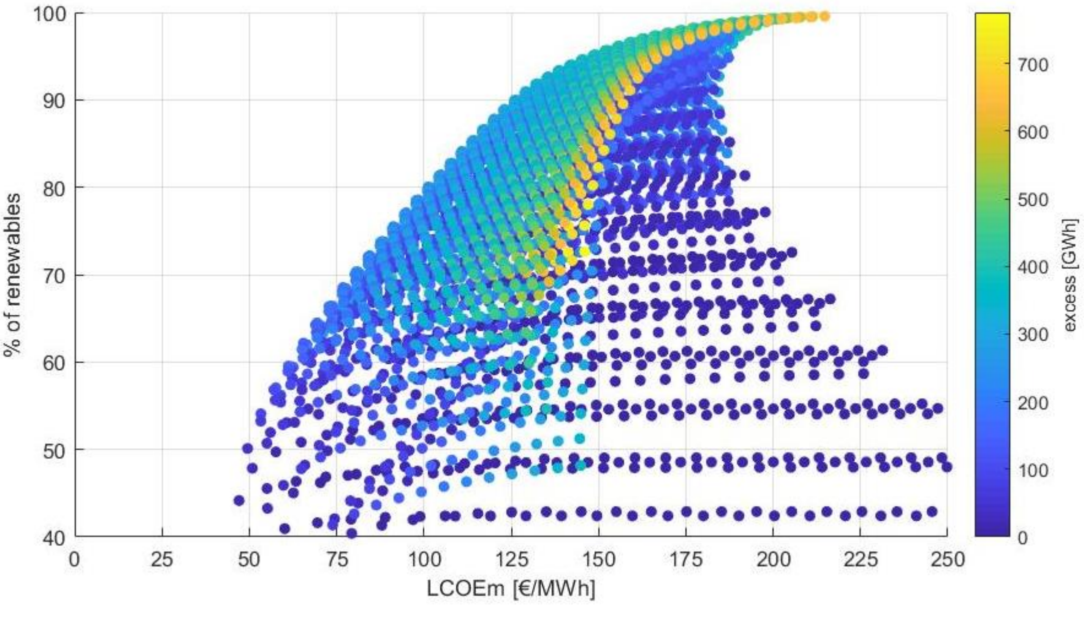

Figure 7.4: % of renewable energy in function of $LCOE_m$ in €/MWh, and relationship with the excess of energy *(colormap), for the case of only renewables*

The results of this case (Table 6), which just has the renewable sources and does not have fuel or the cable, show the point with the lowest cost and the highest amount of renewable energy consumption.

Number of PV modules	101779
Number of wind turbines	17
Total battery capacity	0 MWh
% of renewables	49.92%
$LCOE_m$	48.86 €/MWh
Excess	63.898 GWh

Table 6: Configuration that minimizes the ratio R for the case that only considers renewable sources

These results show that the optimum point is to generate almost 50% of the demand from renewable sources. More energy could be supplied but its cost will be much higher, this is due to the specific distribution of generation at each moment and the use of batteries. The fact that there is no battery can be explained by its expensive cost.

The optimum configuration can also be expressed as 40.71 MWp of PV power and 76.5 MW of wind power. And for two representative days it has the distribution shown in Figure 7.5 and Figure 7.6 . As can be seen, on the 4th of March most of the demand is supplied and one part of the generation exceeds, whereas on the 8th of August the generation only supplies part of the demand. In addition of having more demand on August than on March, in the specific days of the figures there are other considerations to make. Both days seem to have more or less the same amount of PV generation, which indicates that they were sunny days. With the same amount of installed wind power, there was much more generation on the 4th of March than on the 8th of August.

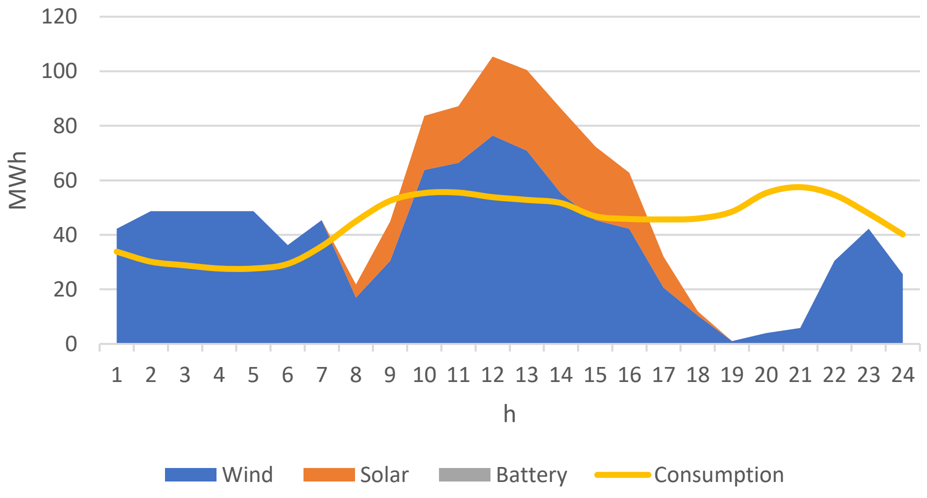

Figure 7.5: Power generation by source and consumption on the 4th March for the case of only renewable sources

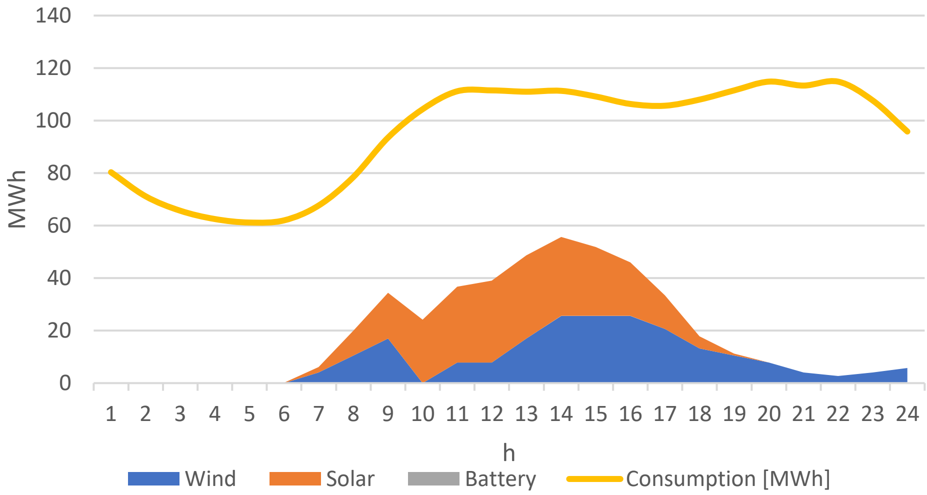

Figure 7.6: Power generation by source and consumption on the 8th August for the case of only renewable sources

7.2.2. Renewable sources and fuel

In this case all the demand is supplied either with renewable sources or with diesel. Simulating several configurations, there can be obtained Figure 7.1, Figure 7.7 and Figure 7.8.

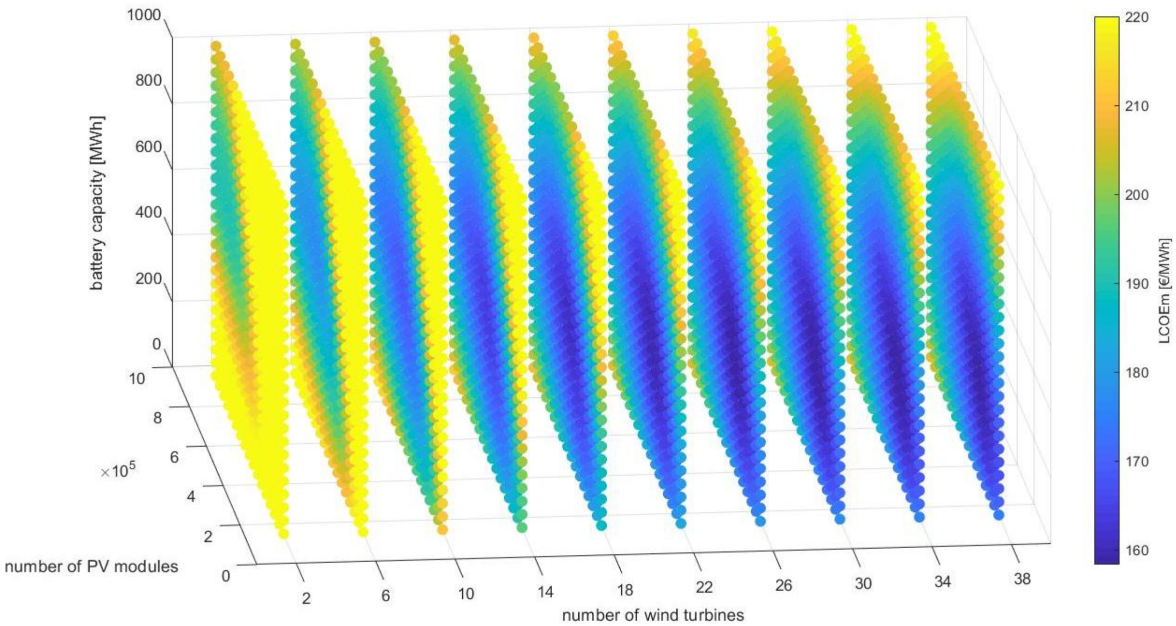

Figure 7.7: $LCOE_m$ in €/MWh (colormap) in function of the system configuration for the case of renewables and fuel

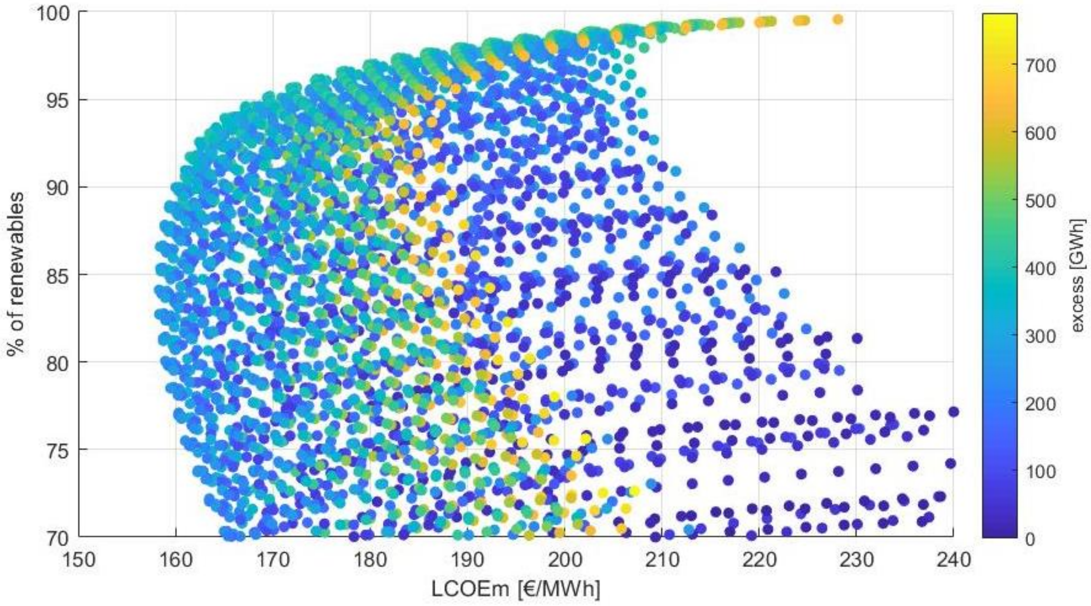

Figure 7.8: % of renewable energy in function of $LCOE_m$ in €/MWh, and relationship with the excess of energy *(colormap), for the case of renewables and fuel*

Each source has a distinctive cost, and since one objective is to minimize the $LCOE_m$, the less each power source costs the more it will be installed. The addition of diesel being quite expensive and the objective to maximize the penetration of renewables lead to the optimum point shown in Table 7.

Number of PV modules	542203
Number of wind turbines	32
Total battery capacity	482.5 MWh
% of renewables	92.17%
$LCOE_m$	161.41 €/MWh
Excess (max 495 GWh)	342.67 GWh

Table 7: Configuration that minimizes the ratio R for the case that considers renewable sources and diesel

It is quite interesting that the optimum point has around 92% of renewable consumption, this is quite high considering the previous case (Subsection 7.2.1). Diesel is so expensive compared to the other sources, that the renewables are highly requested in the balance. This led to an installation with 216.88 MWp of PV power, 144 MW of wind power and more than 480 MWh of batteries. On the other hand, in spite of the high renewable power, there is still needed 100 MW of diesel with an annual consumption of 38.7 GWh.

The detailed distribution of this configuration is shown below. In Figure 7.9 can be seen that all consumption is supplied with renewables because the only hours that the sources does not generate, the battery supplies the energy stored. An important aspect of this figure is that the peak of production is almost 6 times higher than the demand, which shows that the system may be oversized.

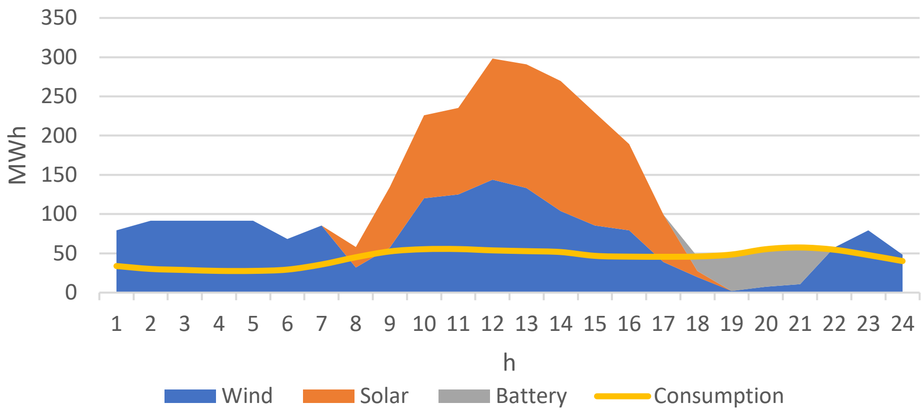

Figure 7.9: Power generation by source and consumption on the 4th March for the case of renewable sources and fuel

On the other hand, in Figure 7.10 the situation is very different. There is also overproduction at the peak but all of the energy stored those hours is later supplied by the battery. The first hours of this day, only fuel supplies electricity. It is for that reason that even though the renewables are oversized, there are still hours that there is no sun or wind and the battery may not be enough.

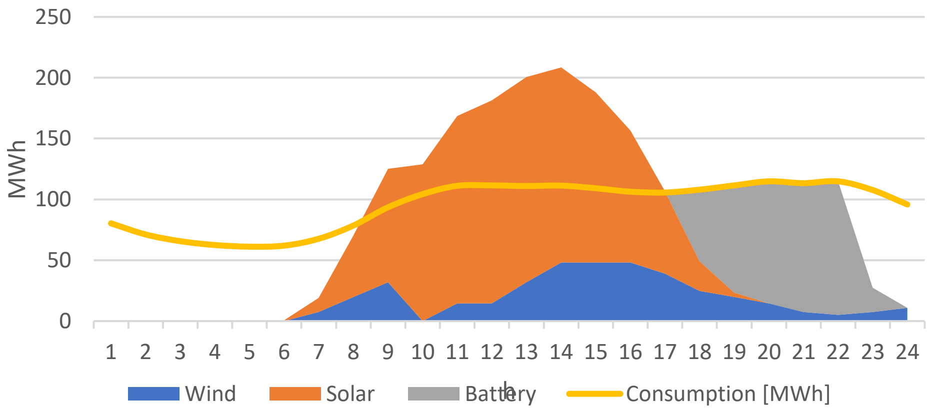

Figure 7.10: Power generation by source and consumption on the 8th August for the case of renewable sources and fuel

Days with overproduction and with underproduction may not be alternated. This type of study where there is underproduction for several consecutive days, shows that it is almost impossible to have an isolated microgrid without fuel for these “emergency” hours. This problem may be solved integrating other sources on the system, such as biomass.

The high renewable consumption also implies a high $LCOE_m$ and excess. $LCOE_m$ is even higher than the current cost of the system, although it almost does not have renewables. And the excess of energy represents 70% of the consumption. If the fuel cost (F from (6.14) and Table 5) were reduced, the optimum point would be very different from this one; first reducing the $LCOE_m$ and then the amount of renewable energy would be closer to the optimum described in Subsection 7.2.1. This amount of renewable energy would be a great solution, but its cost is really high, so it should be studied how to reduce it.

7.2.3. Renewable sources and cable with Mallorca

In this section, energy not supplied by the renewables comes from the cable connecting with Mallorca and indirectly connects with the electrical system of the peninsula. Simulating several configurations, there can be obtained the graphs of Figure 7.1, Figure 7.11 and Figure 7.12. The objective is to maximize the percentage of renewable energy consumed while minimizing its costs.

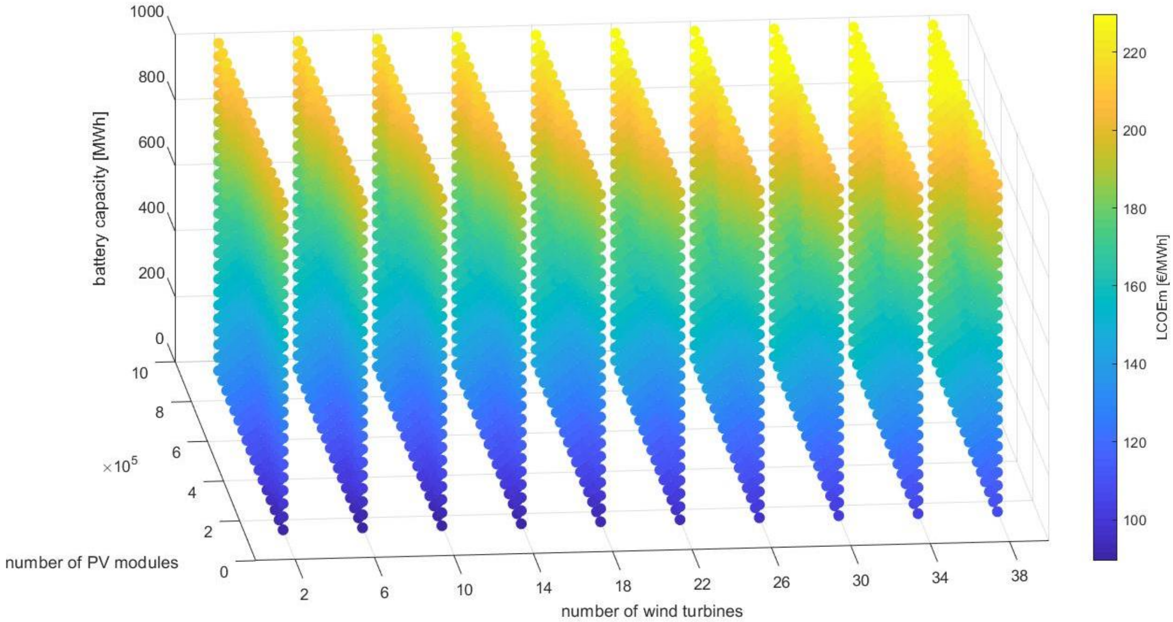

Figure 7.11: $LCOE_m$ in €/MWh *(colormap) in function of the system configuration for the case of renewables and the cable*

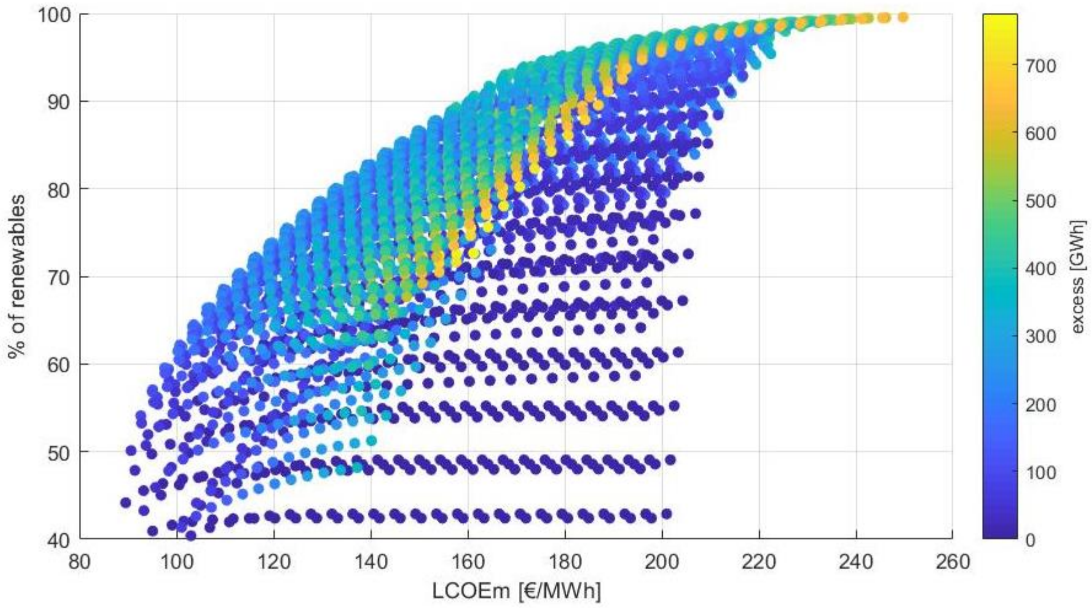

Figure 7.12: % of renewable energy in function of $LCOE_m$ in €/MWh, and relationship with the excess of energy *(colormap), for the case of renewables and fuel*

In this case, due to the comparatively cheap energy from the peninsula, the optimum point has a $LCOE_m$ lower than the current one. So, in order to explore the possibilities of this system, there has been also searched the interval of maximum % of renewables with the current costs.

	Optimum point minimizing the ratio	Maximum % of renewables with current cost
Number of PV modules	249681	395000 – 440000
Number of wind turbines	25	28 – 33
Total battery capacity	64.58 MWh	310 – 340 MWh
% of renewables	67.24%	84.72 – 85.06 %
$LCOE_m$	107.55 €/MWh	144.5 – 145.4 €/MWh
Excess (max 495 GWh)	185.34 GWh	249.6 – 303.4 GWh

Table 8: Configuration that minimizes the ratio R for the case that considers renewable sources and the cable with Mallorca

The configuration of the system at the optimum point, as described on Table 8, has 99.87 MWp of PV power and 112.5 MW of wind power. They seem reasonable amounts of generation power, but with even with a 64.58 MWh storage, the percentage of renewables is not so high. To increase the amount of renewable energy consumed, the $LCOE_m$ should also increase.

Remembering the current system, with a generation cost of 145 €/MWh and less than 5% of renewables. What can be found in this case is that if the current $LCOE_m$ is maintained, with the appropriate configuration of PV modules, wind turbines and batteries, the system can generate up to 85% of the demand with renewable sources. Which does not have any economic impact, but it has a great difference for the planet.

As in previous sections, the distribution of generation versus consumption for the optimum point is shown below in detail. In Figure 7.13 it can be seen that most of the consumption is supplied with renewables, in fact during ⅔ of the day there is an excess of production, a great part of which is not profitable, with a generation peak of 180 MW at midday. Later, the battery will be fully charged, and will be able to supply energy for 2 h, after which the cable will be needed. Figure 7.14 shows a situation where the generation peak is the only moment of the day that consumption is 100% renewable, and most of the time the energy required is supplied by the cable.

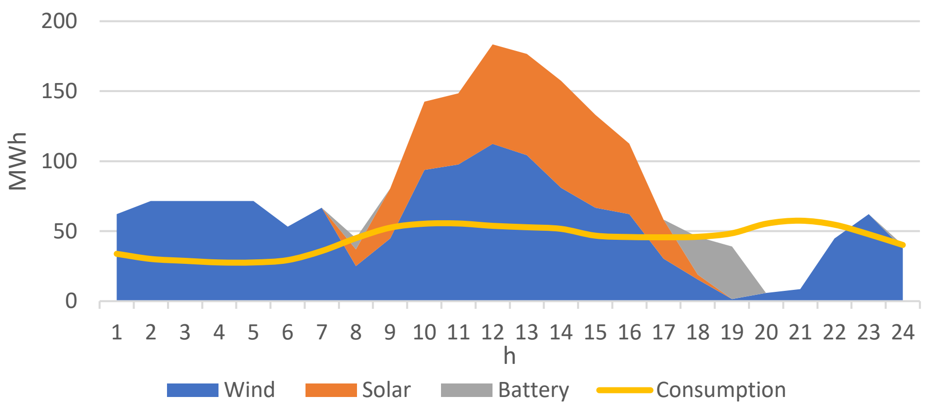

Figure 7.13: Power generation by source and consumption on the 4th March for the case of renewable sources and the cable with Mallorca

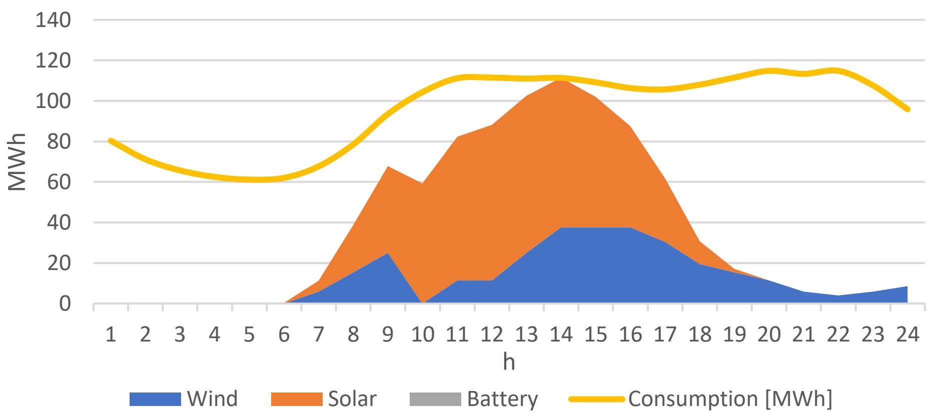

Figure 7.14: Power generation by source and consumption on the 8th August for the case of renewable sources and the cable with Mallorca

7.3. Sensitivity analysis

After finding the results of the optimization analysis it is very important to know if they are a robust design. To do so, there should be carried a sensibility analysis. Giving that the energetic capacities where defined for every hour and the final result of % of renewables is a mean for the whole year, it has some variability but it should not worry due to the big amount of data used. Given that the variables define the configuration of the system, and during its analysis they were already studied; the parameters that are important to verify the sensitivity are the costs.

To verify the sensitivity of the results with respect to the costs, the costs will be slightly changed. Those changes will be done in blocks of power sources according to their future prospects. That way it will not only be obtained conclusions regarding sensibility, but also how the whole project can be useful for future arrangements, or to make the investment in several terms.

Future prospects for 2050 were described on Chapter 5 for each power source. There, it is said that for PV, wind power and batteries their costs will decrease a certain percentage; to apply that, their CapEx and OpEx will be reduced at the same time for each source. For fuel and cable costs, it is said that the most significant variations will take place in the price of the raw material (diesel and electricity) and not in the infrastructure.

To evaluate how the results vary in each situation, it has been used a Design of Experiments (DOE) procedure with 4 factors and 2 levels. Each factor represents a power source, the levels represent the present and future costs, and the experiments are the situations that will be studied. Future costs are referred to the year 2050 following the tendencies explained in Chapter 5.

Experiment	PV costs	Wind costs	Battery costs	Fuel / cable costs
1	-1	-1	-1	-1
2	1	-1	-1	-1
3	-1	1	-1	-1
4	1	1	-1	-1
5	-1	-1	1	-1
6	1	-1	1	-1
7	-1	1	1	-1
8	1	1	1	-1
9	-1	-1	-1	1
10	1	-1	-1	1
11	-1	1	-1	1
12	1	1	-1	1
13	-1	-1	1	1
14	1	-1	1	1
15	-1	1	1	1
16	1	1	1	1

Table 9: DOE for the sensibility analysis

	Level -1 (current costs)	Level 1 (future costs)
PV costs	C_{PV} , Op_{PV}	-45%
Wind costs	C_w , Op_w	-15%
Battery costs	C_{bat} , Op_{bat}	-31%
Diesel costs	F	+900 €/MWh
Cable costs	E	-15 €/MWh

Table 10: Value of the parameters at each level of the DOE

The results of the experiments for the case that considers renewable sources and fuel are listed on Table 11, it should be observed that experiment 16 corresponds to the initial result (the situation studied in Subsection 7.2.2) and so returns the optimum point found previously.

Exp	Nº solar panels	Nº turbines	Total battery capacity [MWh]	% of renewables	$LCOE_m$ [€/MWh]	Excess [GWh]
1	885360	24	899.54	98.71	150.73	402.33
2	767964	33	860.95	98.62	176.67	462.86
3	905133	20	925.25	98.63	153.91	356.25
4	800706	27	883.29	98.53	180.74	395.53
5	827194	29	798.70	98.18	178.33	442.63
6	711450	37	727.95	97.72	201.39	491.38
7	897782	26	813.59	98.30	182.63	441.16
8	721696	35	747.88	97.79	206.99	468.03
9	696499	24	605.04	94.64	122.53	307.43
10	568318	36	549.36	94.38	142.72	406.12
11	760835	18	647.84	94.70	125.64	258.60
12	586725	28	564.24	93.55	146.24	304.45
13	642781	29	506.25	93.17	138.90	355.10
14	568318	36	481.00	93.09	157.75	412.51
15	696394	24	533.30	93.23	143.06	314.31
16	**542203**	**32**	**482.50**	**92.17**	**161.41**	**342.67**

Table 11: Sensibility analysis results for the case of renewable sources and fuel

Whatever the future, the optimum point always has a higher % of renewables than the initial result. This increase in the % of renewables involves a higher $LCOE_m$ in a few cases where the diesel costs increase and, either the battery costs do not change or they decrease but the

PV costs not. Regarding the system configuration, both the number of PV modules and wind turbines are quite variable, going from 568318 to 905133 and from 18 to 37 respectively, highlighting that the number of PV modules will always increase. Battery capacity increases in all possible futures, being able to reach twice the capacity of the initial result having 925 MWh. In spite of this increase in battery capacity, the % of renewables has only small variations, without reaching 99%.

For the case that considers renewable sources and the cable with Mallorca, the results of the experiments are listed on Table 12, and just like before the 16th experiment corresponds to the initial result (the situation studied in Subsection 7.2.3).

Exp	Nº solar panels	Nº turbines	Total battery capacity [MWh]	% of renewables	$LCOE_m$ [€/MWh]	Excess [GWh]
1	363903	22	157,18	73,60	95,65	179,64
2	239720	27	105,91	69,83	100,00	195,75
3	400836	19	194,05	74,55	100,04	153,54
4	261674	24	119,41	69,73	103,65	165,72
5	301028	23	38,27	66,24	88,63	192,32
6	196792	28	28,55	64,70	94,53	209,55
7	317920	21	46,26	66,09	91,78	174,08
8	222945	24	35,62	64,12	97,54	169,90
9	760729	18	493,32	90,98	121,78	276,89
10	270053	29	163,36	74,25	110,68	221,62
11	814245	13	502,95	89,94	122,75	241,53
12	321387	24	203,02	75,25	116,19	174,83
13	322993	24	67,11	69,00	97,26	206,70
14	221350	30	51,51	67,87	104,34	238,08
15	341587	22	80,00	69,15	101,00	188,01
16	**249681**	**25**	**64,58**	**67,24**	**107,55**	**185,34**

Table 12: Sensibility analysis results for the case of renewable sources and the cable

In this case, the % of renewable sources increases in all possible futures except the ones that the costs of the energy from the cable decrease and the battery costs do not decrease, and it can reach almost 91 %. In those situations where the % of renewables decrease, the $LCOE_m$ also does, resulting in a lower ratio R (7.1). In fact, all possible futures have a lower ratio R. In general, the $LCOE_m$ decreases; but on those possible futures in which the battery cost are reduced and the cost of the energy from the cable keeps the same, both the % of renewables and the $LCOE_m$ increase (without exceeding 125 €/MWh). Regarding the system configuration, here also the number of PV modules and wind turbines are quite variable, going from 196792 to 400836 and from 13 to 30 respectively. The number of wind turbines increases only in the situation that the PV costs are maintained and the wind costs are reduced. Battery capacity can have a large increase in those situations that its costs are reduced, but it can also be reduced if the cost of the energy from the cable is reduced and battery costs are kept the same. The two possible situations that the battery capacity is significantly higher than the rest (around 500 MWh), the % of renewables is also significantly higher (around 90%).

8. Budget

8.1. Menorca's new system budget

After finding the optimum point (the result of Subsection 7.2.2 and 7.2.3), here there will be analysed in detail the costs and its payback period, for each case. The initial investment is the sum of all capital costs, assuming that the installation is done at first and it is not progressive. Then, each year there are the expenses of OpEx of all sources and the cost of the energy (either by diesel or from the cable). The current situation can be described as no investment and the annual expenses are found multiplying the current cost of energy generation by the annual consumption.

This results in Table 13 for the cases studied, and it is compared to the current situation that has 71.64 million € of annual expenses.

	Renewables and fuel	Renewables and cable
CapEx PV	291,16	134,08
CapEx wind	205,77	160,76
CapEx battery	188,74	25,26
CapEx fuel	82,33	0
CapEx cable	0	155,63
OpEx PV	4,55	2,10
OpEx wind	5,64	4,41
OpEx battery	16,25	2,17
OpEx fuel	2,79	0
OpEx cable	0	13,38
Fuel cost	12,11	0
Cost of energy from the cable	0	7,28
Initial investment	768,01	475,74
Annual expenses	41,35	29,35

Table 13: Final costs in million €, for each case

Giving the lifetime of 20 years for the whole system, the case of renewables and fuel will require 1595 million €, the case of renewables and the cable with Mallorca will need 1063 million € and the current system would spend 1433 million €. With respect to the current situation, the payback period is 25.35 years for the case of renewables and fuel, and 11.25 years for the case of renewables and the cable with Mallorca.

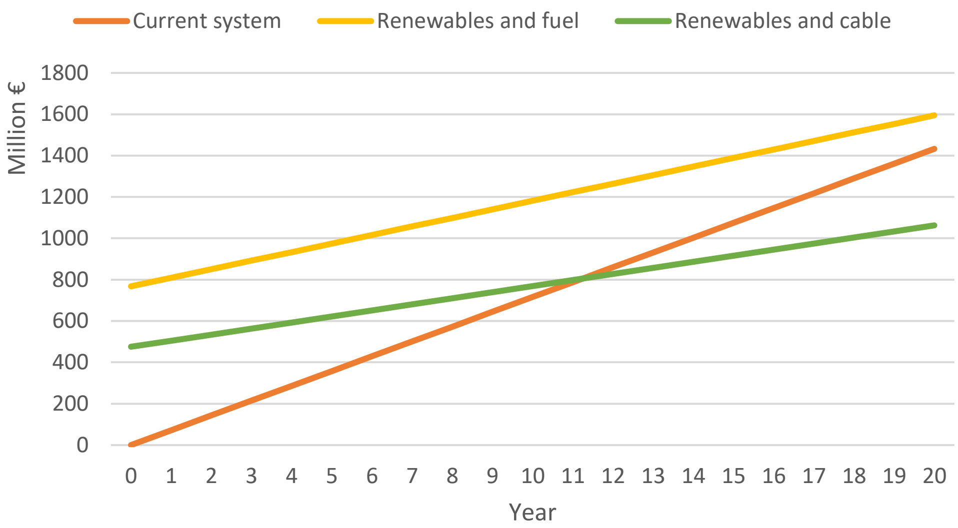

Figure 8.1: Accumulated costs over the lifetime for each system

8.2. Thesis budget

The budget of this thesis has been elaborated taking into account office equipment, software and human resources. Office equipment refers to a computer, which is used to do the research, to design the power system, to run the analysis and to write the thesis. Software used includes Word to write the thesis, Excel and Matlab, to design the power system and to run the analysis. Human resources are referred to the cost of hours dedicated by an engineering student, taking into account that the thesis has a workload of 12 ECTS (with 1 ECTS = 25 h). All costs are showed in Table 14, giving a total budget of 4249 €.

Concept	**Unitary cost**	**Units**	**Total**
Computer	900 €	1	900 €
Microsoft Office license	149 €	1	149 €
Matlab annual license	800 €	1	800 €
Human resources	8 €/h	300	2400 €
Total			4249 €

Table 14: Thesis budget

9. Environmental impact

In this section there is a study of the environmental impact of the new power system. There will be analysed each power source separately.

Solar energy is pollution-free during its operation, although the production of PV panels has a certain environmental impact. Nowadays, PV modules recover the energy necessary for their manufacture in a period of between 6 months and 1.5 years. Taking into account that their average useful life is over 25 years, greenhouse gas emissions throughout the life cycle for photovoltaics are close to 46 g/kWh. A 1 kW photovoltaic system saves the combustion of approximately 77 kg of coal, prevents the emission of about 136 kg of CO_2 into the atmosphere, and saves the use of about 400 liters per month of water. In addition to energy, many dangerous substances are used in the photovoltaic panel manufacturing process (for example hydrochloric acid, sulfuric acid, nitric acid, hydrogen fluoride, 1,1,1-trichloroethane, and acetone). Utility-scale solar systems also make a negative impact on the land depending on the location, which includes land degradation and habitat loss for both flora and fauna [58].

Wind power is also pollution-free during its operation, but has a wide variety of environmental impacts associated. Wind power is one of the cleanest energies nowadays, according to the IPCC wind turbines have a median value of between 15 and 11 gCO_2eq/kWh, in contrast with 40 - 50 gCO_2eq/kWh of PV modules. But wind power not only reduces CO_2 emissions, it also reduces the amount of water consumption because wind energy only needs 0.004 l/kWh. Wind energy is the energy source that is most compatible with animals and human beings in the world, there have been bird and bat deaths from collisions with wind turbines but this situation is quite unusual. The most critical environmental impact of wind turbine is the noise pollution, and it can be due to aerodynamical or mechanical causes. There is also a visual impact. Wind farms located offshore will also impact fish and other marine wildlife [68].

Lithium-ion batteries help promote sustainable actions, but it is important to mention that the batteries themselves are not yet “environmental friendly”, although they are ahead of fossil fuels. Most of the energy used to produce the batteries is used in mining and manufacturing them. Mining can have some collateral problems such as toxic chemical leaks that pollutes the surroundings and kill wildlife. The other critical part of the environmental impact is recycling, some research is going on and some companies offer to recycle batteries, but the result is that only 5% of them are being recycled. In general, lithium-ion batteries can have an impact of 39 - 196 $kgCO_2eq/kWh$ [70].

Diesel generators have constant CO_2 emissions during operation, which produces a huge environmental impact. Specifically, diesel generators emit around 268 gCO_2eq/kWh. Diesel exhaust contains more than 40 toxic air contaminants, including many known or suspected cancer-causing substances (such as benzene, arsenic, and formaldehyde). It also contains other harmful environmental pollutants, including nitrogen dioxide (NO_2), currently the single most important ozone-depleting emission, carbon monoxide (CO), nitric oxide (NO), and sulfur dioxide (SO_2) [71].

In analysing the environmental impact of the cable with Mallorca, there are two components: the energy production and the cable itself. During installation, maintenance and decommissioning phases of the cable, the main environmental effects include physical habitat disturbances, sediment resuspension, chemical pollution and underwater noise emission. When the cable is operating, the effects are: changes in electromagnetic fields, heat emission, risk of entanglement, chemical pollution, and creation of artificial reef and reserve effects [72]. Regarding the generation of the energy, since it comes from the peninsula where 37.5% of consumption in 2019 was from renewable sources [73], it will have the equivalent emissions.

Conclusions

This thesis has addressed the design of a hybrid power system for Menorca, in order to make it more renewable and achieve the sustainability objectives set by Europe and the Spanish government. The hybrid system considered includes PV power, wind power, batteries, and fuel (diesel) or a cable that connects with Mallorca. Then, it has been carried out a study to find how can be distributed the generation between its sources to achieve as much renewable penetration as possible taking into account the average cost of generation.

Renewable sources by themselves could supply 50% of the total demand of Menorca with a cost of 49 €/MWh. It should be noted that when trying to reach 100% of renewables, the costs have a huge increase, making it not the best option from an economic perspective. This occurs because there are days with some of the higher demands of all year that, due to climatological circumstances, almost no energy is produced from PV and wind. And so, the amount of PV modules, wind turbines and battery capacity increases exponencially to be able to supply those few hours.

When the system includes the renewable sources and fuel, the optimum point has an important amount of renewable energy, and the costs also heavily increase. This may be because of diesel is very expensive that till the renewables reach a balance with it, they have produced almost all the required energy. That situation offers an appropiate amount of renewables, but it has a higher cost than nowadays, which is already high compared to the peninsula. So there should be studied other ways of reaching that much renewable production, for example choosing a cheaper source such as gas. In future configurations the % of renewables will increase and the costs can decrease around 20 €/MWh.

When the system includes the renewable sources and the cable with Mallorca, the optimum point shows a very different configuration. This point is closer to the optimum point where only renewables where considered, and its costs are not as high as nowadays. The problem of this point is that it does not achieve the goal of minimum 85% of renewables (produced on the island). Although, when considering the current system (with a cost of 145€/MWh and almost no renewable energy), there can be found situations with up to 85% of renewables with the current cost. Future conditions result in higher amount of renewables and a possible reduction of costs, which in the best situation implies 90% of renewable energy and a cost of 122 €/MWh.

In general, from an economic perspective, it might not be the best option to have a system with 85% of renewable energy. But since future costs of renewables are expected to decrease, it can be interesting to study how a progressive investment influences the affordability of higher amounts of renewables.

Thank-you note

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ANNEX

Annex A: Detailed explanation of photovoltaics

The photovoltaic effect is the generation of voltage and electric current in a material thanks to the exposure to light. The solar cells are composed of two types of semiconductors that form the p-n junction. The electrons present in the valence band absorb the energy that the light gives to them. When that energy is enough to overcome the energy gap for excitation, the electrons jump to the conduction band and become free. Due to the electric field formed by the p-n junction, the excited electrons move from the p-side to the n-side creating an electric current in the cell.

In radiation energy, it is important to know two definitions: irradiance is the instantaneous power received at a given location [W/m^2], irradiation is the amount of solar energy received in a period of time [$W{\cdot}h/m^2$]. There are different irradiance and irradiation components to care about in the PV effect: the direct component is the energy that comes from the direct incidence of sunlight on the cell, the diffuse component is the energy incident on the cell from the dispersion of sunlight on atmosphere components, the reflected component is the light reflected by the earth's surface that ends on the cell. The total irradiation on the cell is the sum of all the previous components. The main advantage of solar energy is that the available energy is much greater than what is needed, in this case, the solar energy reaching the Earth's surface is 122 PW and the power consumed by humans was only 13 TW in 2005 [59].

The voltage and current of the cell follow the curve in Figure A.1. This curve varies depending on some parameters such as temperature and solar radiation, if temperature increases the cell is less efficient and the V_{oc} decreases, if the solar radiation increases the current also increases [56]. The temperature coefficient is a usual parameter and it is proportional to the temperature. The maximum power point, defined by a certain voltage and current, appears with the subscript MP.

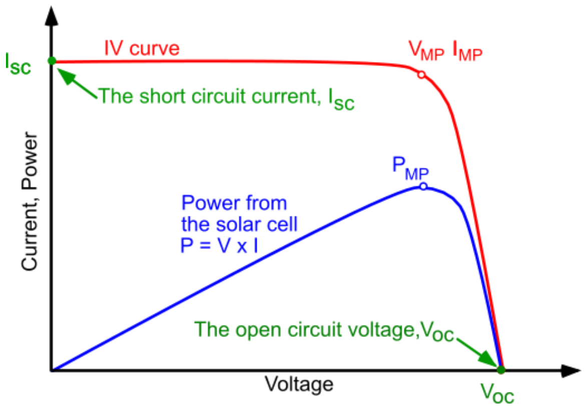


Figure A.1: Current-Voltage and Power-Voltage graphs of a PV cell

In a PV module, the cells have parallel and series connections. In the same way, in a system, the PV modules can be connected in parallel and series. Modules connected in parallel increase the current and modules connected in series increase the voltage (Figure A.2). It is important to mention that high values of current will need thicker cables and will have more losses, so it is important to make a balance between voltage and current.

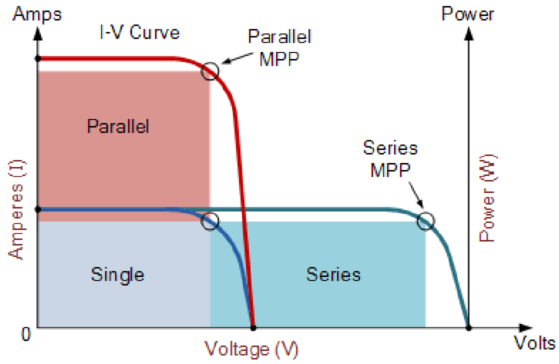


Figure A.2: Current-Voltage graph with connections of PV cells or PV modules

PV cells can be made of different materials. Monocrystalline silicon cells are more efficient (14 – 16 %) and more expensive than most other types of cells. Polycrystalline silicon cells are the most popular, they have good performance (14% efficiency) and are less expensive. Amorphous silicon is less efficient (7%) and has a reduced cost. Thin-film technologies reduce the amount of active material in a cell, reducing the environmental impact but they are approximately twice as heavy as crystalline silicon panels. Cadmium telluride is the thin film equivalent to crystalline silicon in cost/watt. Copper indium gallium selenide has the highest efficiency (20%) among all commercially significant thin film materials. PERC (Passivated Emitter Rear Cell) technology offers an increase in efficiency with respect to all the previous materials, this is due to the exploitation of the energy that penetrates until the aluminium layer (Figure A.3), so it has higher production with low irradiance and lower temperature coefficient [57].

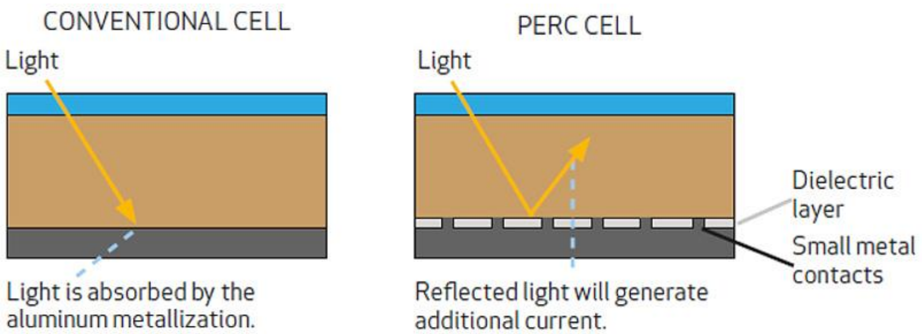


Figure A.3: Comparison between conventional and PERC cell

Annex B: Detailed explanation of wind power

The wind hits the turbine’s blades and the lift force on the blade causes a rotating force on the rotor. The blades make the low-speed shaft to roll, and the rotation enters the gearbox. The gearbox increases the rotational speed and drives the generator. Finally, the generator uses magnetic fields to convert rotational energy into electrical energy [60], [61]. In wind power systems there are also other components besides the turbines. The system may need an inverter (AC/AC) and storage systems, also wiring and protections are essential. To optimize wind speed and avoid possible problems, turbines must be spaced approximately 5 to 10 rotor diameters apart from each other.

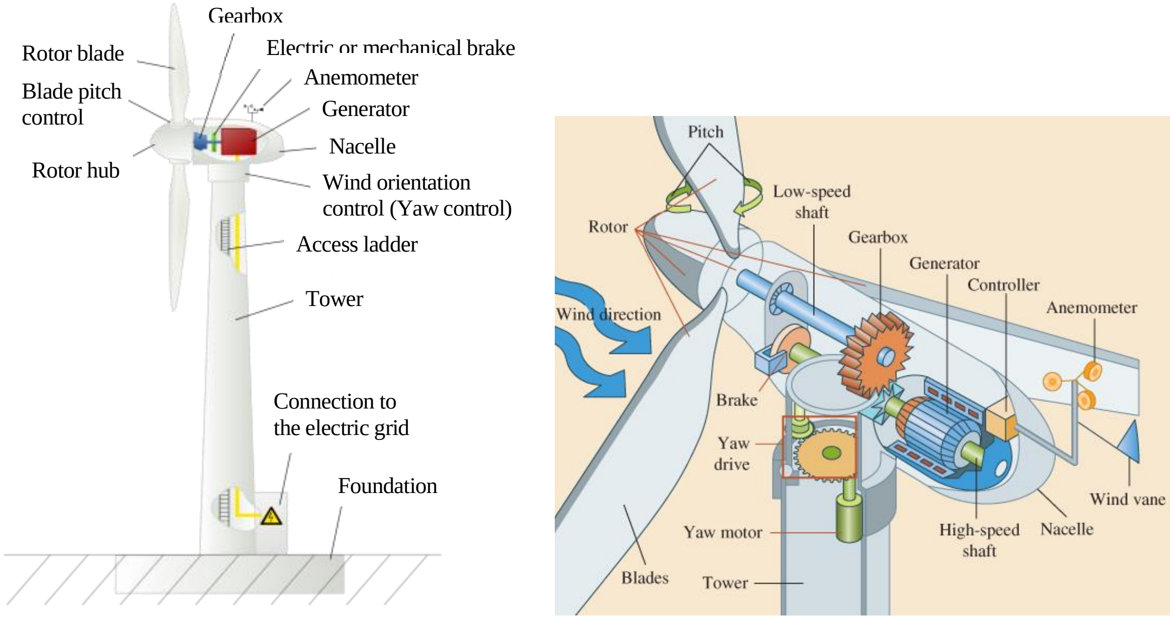


Figure A.4: Components of the wind turbine

Wind turbines can have several designs according to the axis direction and the number of blades. Horizontal axis turbines are the most common, they have the blades perpendicular to the wind, as can be seen in Figure A.4. Since they need to be oriented towards the wind, large turbines generally use a wind sensor coupled with a yaw system. This type of turbines takes advantage of strong winds at a bigger height, producing a lot of power. There are two ways to place the rotor with respect to the tower, in front (upwind) or behind (downwind) the tower; upwind designs are more frequent because they reduce the fatigue load. When the wind is blowing downwards, the turbine structure may suffer from metal fatigue which could lead to a structural failure, for that reason they require careful control. The main disadvantage of horizontal axis turbines is that it requires heavy construction, they are difficult to transport and install, and have a great visual impact on the environment [62], [63].

Vertical axis turbines have the main rotor shaft arranged vertically. This type of turbine does not need to be positioned directly into the wind to be effective, so they are less affected by frequent wind direction changes. The shaft is mounted near ground level, an advantage of this is that maintenance of the turbine is easier and can be installed at locations such as rooftops. But due to its lower elevation and lower wind speeds, the efficiency is also lower and produces much less energy. Some advantages of this type of turbines are that they do not need a powerful tower structure and are easily avoided by birds, unlike horizontal axis turbines. Two designs can be distinguished: Savonius and Darrieus. Savonius wind turbines require small wind speeds and have a relatively low performance; these are drag-type devices with two or more scoops (they are used in anemometers for example) and they are self-starting if there are at least three scoops. Darrieus wind turbines have a relatively good efficiency but it is unstable, which can be solved by using three or more blades to give solidity to the rotor; they also need some external power supply or additional Savonius rotor to start spinning [62], [63].

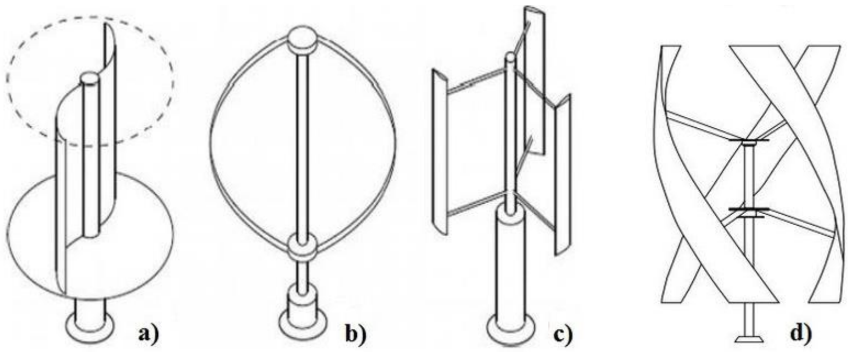
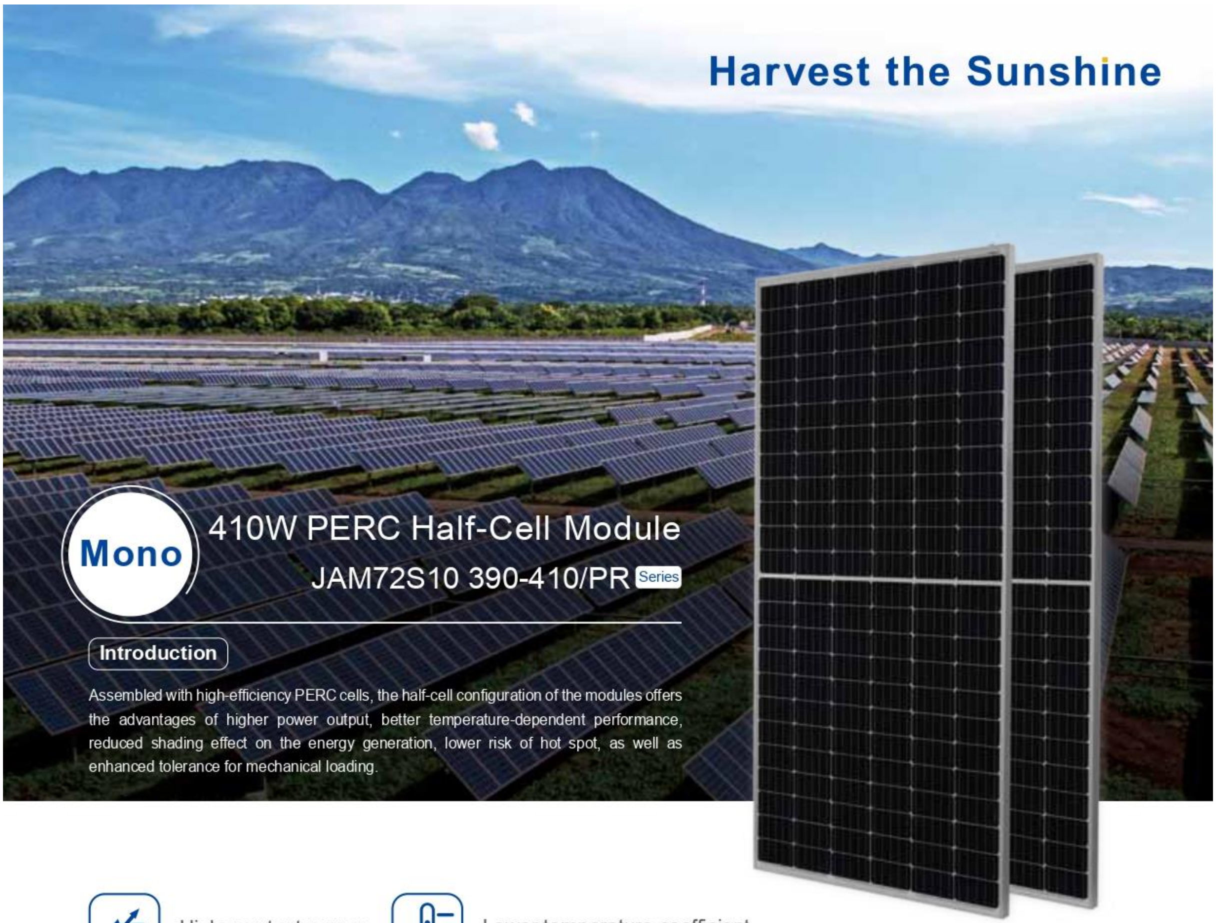


Figure A.5: Types of vertical axis turbines: Savonius (a), Darrieus-rotor (b), H-Darrieus (c) and helical Darrieus (d) [64]

Wind turbines usually have three blades, but they can have from one to several blades. Two-bladed turbines have the advantage of saving the cost of one rotor blade and its weight and reducing the turbine weight by 30%, but they require higher rotational speed to produce the same output and the rotor has to be able to tilt in order to avoid too heavy shocks to the turbine when a rotor blade passes the tower. One-bladed turbines have the same advantages as the two-bladed turbines, but the problems of the two-bladed turbine apply to an even larger extent [65], [66]. Apart from the number of blades, the shape of the blades (defined in their design) is very important to assure the correct performance of the turbine and make it as efficient as possible [67].

Depending on the location of the wind turbine, it can be classified as onshore (on land) or offshore (on water). Onshore turbines are located on land and near the power grid or the load, While offshore turbines are usually located and far away from the grid on the ocean (deep-water areas), or on inshore water areas such as lakes, fjords, and coastal areas. Offshore turbines are in a hostile environment, which means that they have stronger winds due to the location (and produce more energy) but at the same time they can be damaged by the marine conditions. Most offshore wind turbines have fixed-foundation since floating wind turbines are in the early phase of development. This structure has much higher cost and it is difficult to install and maintain (waves can damage the tower and the marine weather can cause corrosion). Although, due to space limitations, offshore wind is seen as a future trend.

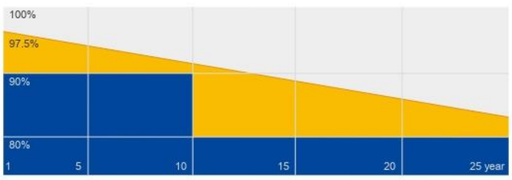
Annex C: Technical sheet PV module 1



- Higher output power
- Lower temperature coefficient
- Less shading effect
- Better mechanical loading tolerance

Superior Warranty

- 12-year product warranty
- 25-year linear power output warranty



JA Linear Power Warranty ■ Industry Warranty

Comprehensive Certificates

- IEC 61215, IEC 61730
- ISO 9001: 2015 Quality management systems
- ISO 14001: 2015 Environmental management systems
- OHSAS 18001: 2007 Occupational health and safety management systems
- IEC TS 62941: 2016 Terrestrial photovoltaic (PV) modules – Guidelines for increased confidence in PV module design qualification and type approval

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JA Solar reserves the right of final interpretation.

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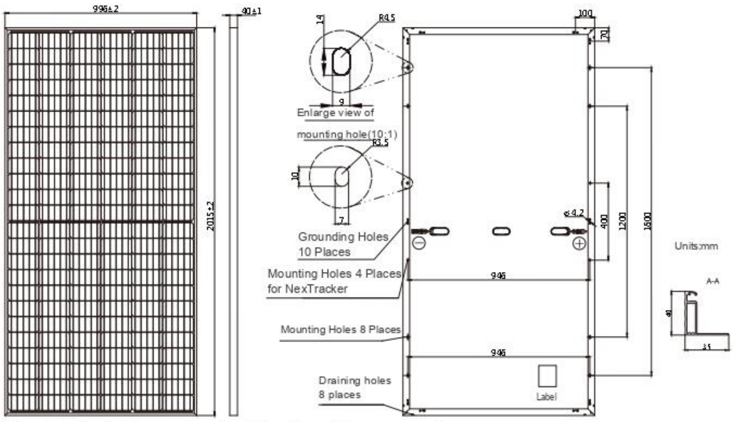
JAM72S10 390-410/PR Series

MECHANICAL DIAGRAMS



Remark: customized frame color and cable length available upon request

SPECIFICATIONS

Cell	Mono
Weight	22.7kg±3%
Dimensions	2015±2mm×996±2mm×40±1mm
Cable Cross Section Size	4mm²
No. of cells	144（6×24）
Junction Box	IP68, 3 diodes
Connector	QC 4.10-35
Cable Length (Including Connector)	Portrait:300mm(+)/400mm(-); Landscape:1200mm(+)/1200mm(-)
Packaging Configuration	27 Per Pallet

ELECTRICAL PARAMETERS AT STC

TYPE	JAM72S10 -390/PR	JAM72S10 -395/PR	JAM72S10 -400/PR	JAM72S10 -405/PR	JAM72S10 -410/PR
Rated Maximum Power(Pmax) [W]	390	395	400	405	410
Open Circuit Voltage(Voc) [V]	48.91	49.21	49.50	49.81	50.12
Maximum Power Voltage(Vmp) [V]	40.55	40.85	41.17	41.46	41.76
Short Circuit Current(Isc) [A]	10.16	10.21	10.26	10.32	10.37
Maximum Power Current(Imp) [A]	9.62	9.67	9.72	9.77	9.82
Module Efficiency [%]	19.4	19.7	19.9	20.2	20.4
Power Tolerance	0~+5W				
Temperature Coefficient of Isc(α_Isc)	+0.051%/℃				
Temperature Coefficient of Voc(β_Voc)	-0.289%/℃				
Temperature Coefficient of Pmax(γ_Pmp)	-0.350%/℃				
STC	Irradiance 1000W/m², cell temperature 25℃, AM1.5G				

Remark: Electrical data in this catalog do not refer to a single module and they are not part of the offer.They only serve for comparison among different module types.
*For NexTracker installations static loading performance: front load measures 2400Pa, while back load measures 2400Pa.

ELECTRICAL PARAMETERS AT NOCT

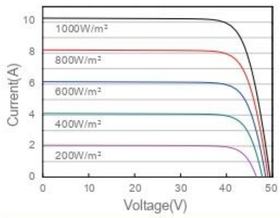
TYPE	JAM72S10 -390/PR	JAM72S10 -395/PR	JAM72S10 -400/PR	JAM72S10 -405/PR	JAM72S10 -410/PR
Rated Max Power(Pmax) [W]	289	292	296	300	303
Open Circuit Voltage(Voc) [V]	45.04	45.30	45.56	45.81	46.06
Max Power Voltage(Vmp) [V]	37.29	37.52	37.76	38.03	38.28
Short Circuit Current(Isc) [A]	8.18	8.23	8.28	8.33	8.38
Max Power Current(Imp) [A]	7.74	7.79	7.84	7.88	7.93
NOCT	Irradiance 800W/m², ambient temperature 20°C, wind speed 1m/s, AM1.5G				

OPERATING CONDITIONS

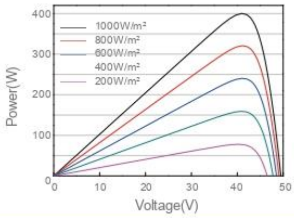
Maximum System Voltage	1000V/1500V DC(IEC)
Operating Temperature	-40℃~+85℃
Maximum Series Fuse	20A
Maximum Static Load,Front*	5400Pa
Maximum Static Load,Back*	2400Pa
NOCT	45±2℃
Application Class	Class A

CHARACTERISTICS

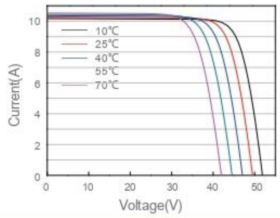
Current-Voltage Curve JAM72S10-400/PR



Power-Voltage Curve JAM72S10-400/PR

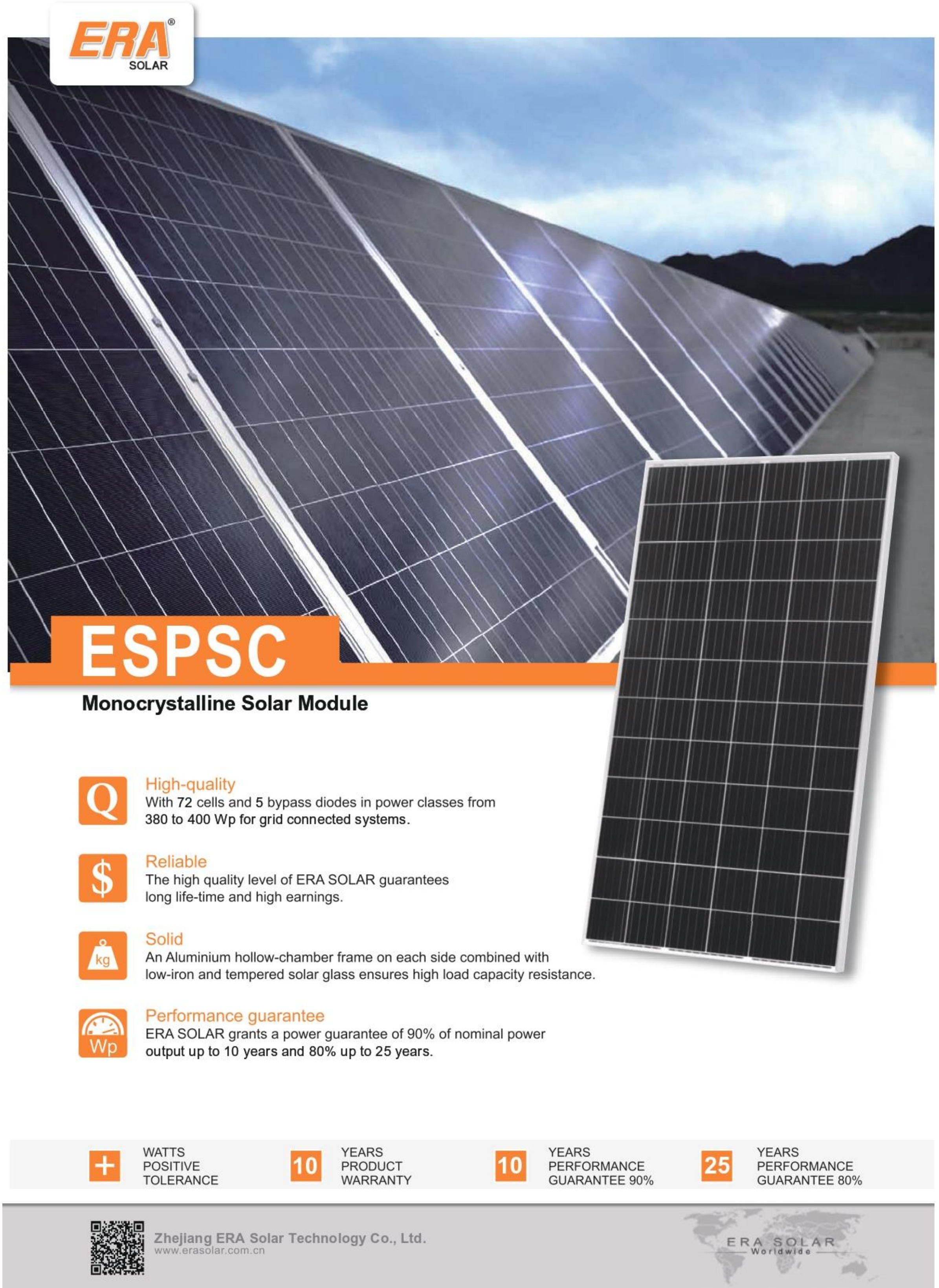


Current-Voltage Curve JAM72S10-400/PR



Premium Cells, Premium Modules Version No. : Global_EN_20190703A

Annex D: Technical sheet PV module 2


ERA SOLAR

ESPSC

Monocrystalline Solar Module

High-quality
With 72 cells and 5 bypass diodes in power classes from 380 to 400 Wp for grid connected systems.

Reliable
The high quality level of ERA SOLAR guarantees long life-time and high earnings.

Solid
An Aluminium hollow-chamber frame on each side combined with low-iron and tempered solar glass ensures high load capacity resistance.

Performance guarantee
ERA SOLAR grants a power guarantee of 90% of nominal power output up to 10 years and 80% up to 25 years.

+ WATTS POSITIVE TOLERANCE

10 YEARS PRODUCT WARRANTY

10 YEARS PERFORMANCE GUARANTEE 90%

25 YEARS PERFORMANCE GUARANTEE 80%

Zhejiang ERA Solar Technology Co., Ltd.
www.erasolar.com.cn

ERA SOLAR Worldwide

ESPSC

Monocrystalline Solar Module

SPECIFICATIONS

Dimensions	1979 x 1002 x 40mm
Weight	22.5 kg
Frame	Aluminium hollow-chamber frame on each side
Glass	Low-iron and tempered glass 3.2 mm
Cells	72 pcs Mono PERC (158.75 x158.75 mm)
Cell Embedding	EVA
Back-Foil	FEVE / PET / FEVE
Junction Box	TÜV certified
Cable	4 mm² solar cable 2 x 900 mm or Customized Length
Temperature Range	-40°C ... +85°C
Load Capacity	5400 Pa(IEC 61215),40mm

Application class	Class A
Electrical protection class	Class II
Fire safety class	Class C
Product warranty	10 years
Power Guarantee	10 years 90% 25 years 80%

Packaging Configuration

(Two pallets = One stack)
27pcs/pallet, 54pcs/stack,
594pcs/40'HQ Container

CHARACTERISTICS

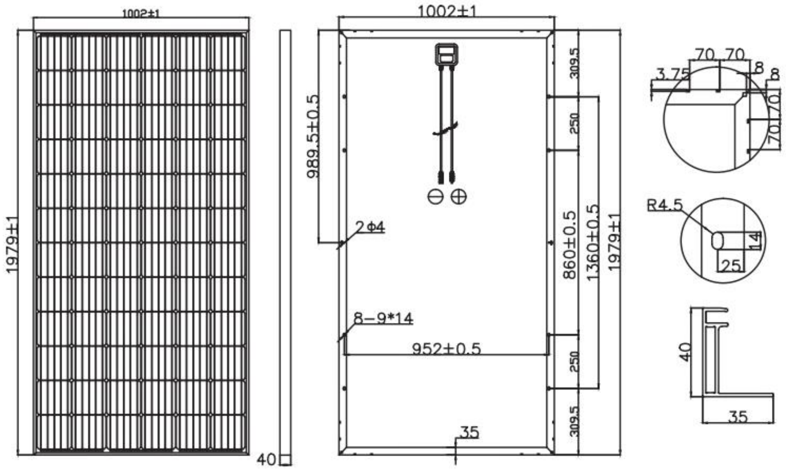
Max. System Voltage	1000V/DC
Temperature-Coefficient I_{SC}	+0.02973%/°K
Temperature-Coefficient V_{OC}	-0.38038%/°K
Temperature-Coefficient P_{mpp}	-0.57402%/°K
NOCT***	45°C

CERTIFICATES

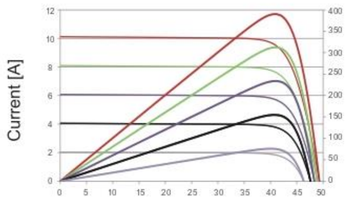
IEC 61215 edition 2 (TÜV Nord)
(TÜV Rheinland)
IEC 61730 MCS INMETRO
CE CEC SALT-MIST
UL1703 CSA
PID Resisitant

INSURANCE

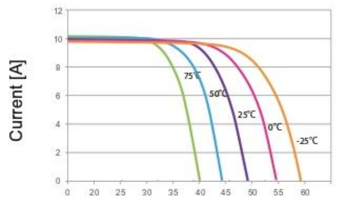
Chubb



CURRENT-VOLTAGE CURVES



Voltage [V]
Module characteristics at constant module temperatures of 25°C and variable levels of irradiance



Voltage [V]
Module characteristics at variable module temperatures and constant module irradiance of 1.000 W/m²

ESPSC TYPE	380M	385M	390M	395M	400M
Power Class	380Wp	385Wp	390Wp	395Wp	400Wp
Max. Power Voltage (V_{mpp})* at STC**	40.5V	40.8V	41.1V	41.4V	41.7V
Max. Power Current (I_{mpp}) at STC	9.39A	9.44A	9.49A	9.55A	9.60A
Open Circuit Voltage (V_{OC}) at STC	48.9V	49.1V	49.3V	49.5V	49.8V
Short Circuit Current (I_{SC}) at STC	9.75A	9.92A	10.12A	10.23A	10.36A
Module Efficiency	19.16%	19.42%	19.67%	19.92%	20.17%

* MPP: Maximum Power Point
** STC (Standard Test Conditions): 1000W/m², 25°C, AM 1.5
*** Normal Operating Cell Temperature

ETSEIB

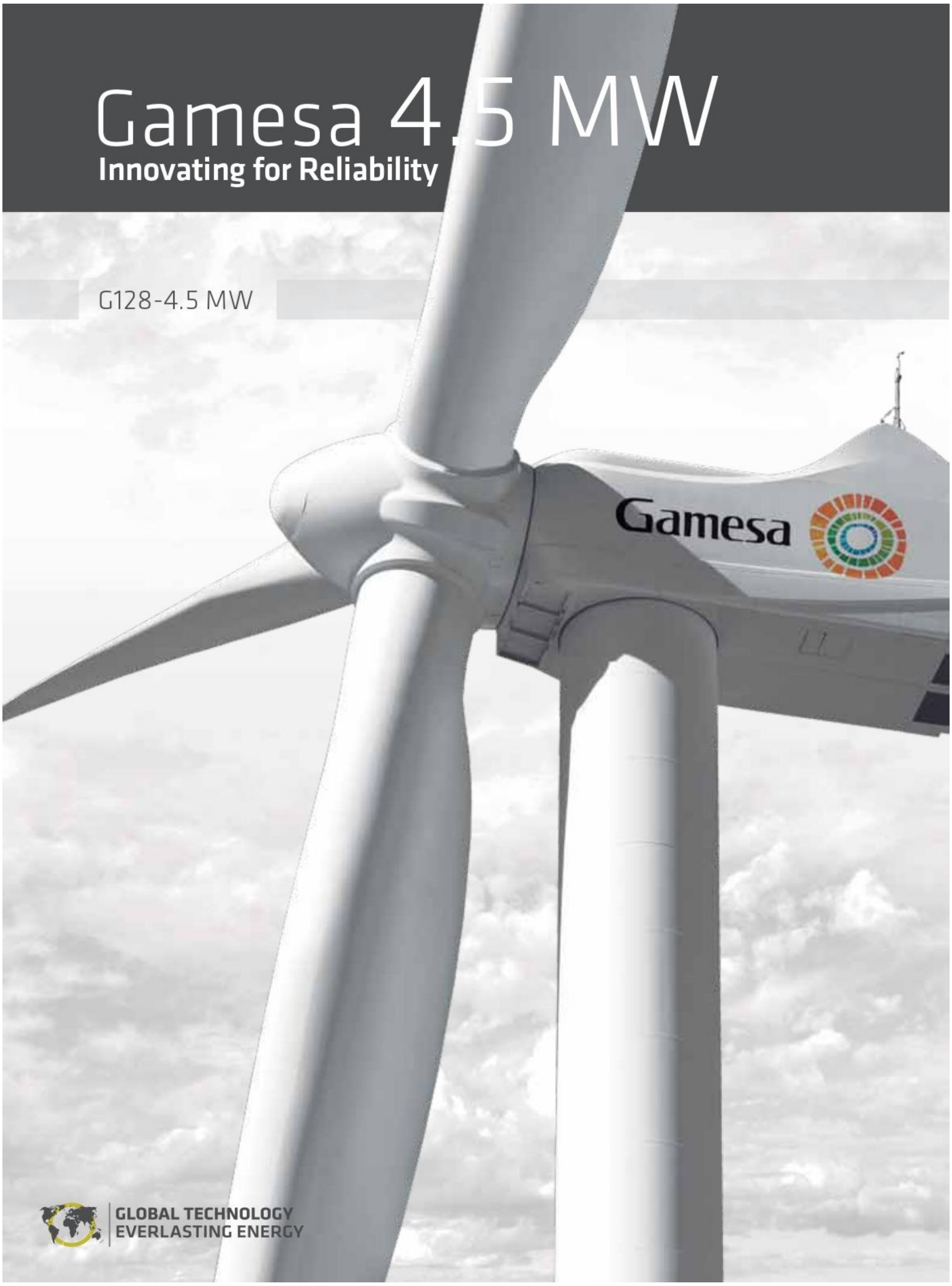
Annex E: Wind analysis

```
load('Data')
dat_w = Data ;    % ---> data every hour
v = dat_w+1e-5 ; % Sum small number to make sure v is
never =
p1 = wblfit(v) ; % Use the weibull fitting to obtain c
and k
c = p1(1);k=p1(2) ; % Save c and k variables
% histogram definition
interval_v = 0.1; % width interval
vv = interval_v:interval_v:30 ; % interval definition
wf1 = wblpdf(vv,c,k) ; % calculation of the weibull
[Nv_dist v_dist] = hist(v,vv) ; % histogram
Nv_dist_pu = Nv_dist/(interval_v*sum(Nv_dist)) ; %
normalization
% Plots
figure(1) ; subplot (2,2,1);
plot (v) ;
xlabel ('Sample','FontSize',16) ;
ylabel ('Wind speed', 'FontSize',16) ;
grid on ;
title('Raw data','FontSize',16) ;

subplot(2,2,2) ;
hist(v,100) ;
title('Histogram','FontSize',16) ;

subplot(2,2,[3 4]) ;
plot(vv,wf1) ;
hold on ;
plot(v_dist,Nv_dist_pu);
ylabel('Probability function','FontSize',16) ;
xlabel('Wind speed','FontSize',16) ;
grid on ;
legend('Weibull distribution','Raw data histogram') ;
title('Weibull distribution and raw data
histogram','FontSize',16) ;
```

Annex F: Technical sheet wind turbine



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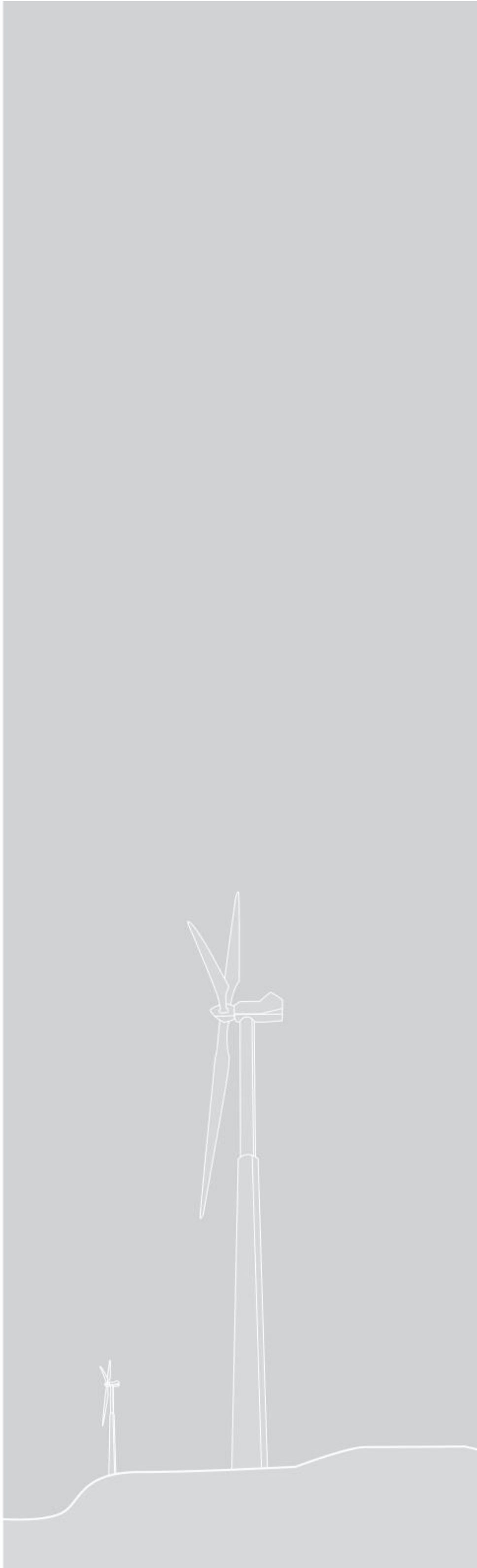
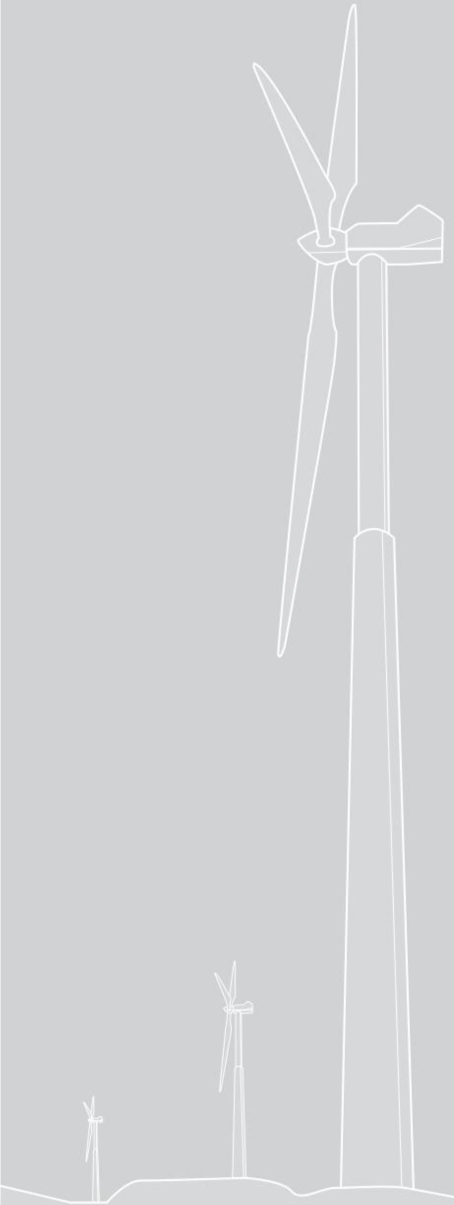




Innovation & Reliability

Once again, Gamesa has demonstrated that it has the knowledge, experience and resources needed to develop wind turbines capable of extracting maximum power from the wind.

The Spanish company has taken a leap forward in one of its biggest, most ambitious technological challenges to date. Gamesa has designed, developed and manufactured its new generation of wind turbines, the Gamesa 4.5 MW platform.

With this new product platform, Gamesa intends to position itself at the forefront of the multi-megawatt platform segment.

By using assembly equipment and transport methods similar for those used in other Gamesa platforms, the company can provide access of the Gamesa 4.5 MW to a wide variety of sites.

Its innovative modular design and technology ensure maximum reliability and meet the most demanding grid connection regulations and the most restrictive environmental standards.

Gamesa 4.5 MW designed to fully meet all client needs

4

Offers superior reliability:

- Nacelle and blades modular design focused on minimizing inactive time.
- Drive train with no high-speed rotating components.
- Exhaustive validation and testing plan, as well as the first operational prototype since 2009.

Complies with similar logistics and construction requirements as those of the Gamesa 2.0 MW:

- Modular design of the nacelle and blades to optimize transport and logistics.
- The heaviest module weighs less than the weight of a 2-MW nacelle.
- Gamesa FlexiFit®:
  The add-on crane attaches to nacelle to simplify and expedite assembly and maintenance.

Optimizes cost of energy (CoE):

- Higher production for projects with limited space.
- Optimization of energetical positions.
- Potential savings in project civil works.
- Version with 5.0 MW nominal power available depending on the site.

Complies with the most demanding grid connection requirements:

- Gamesa GridMate®:
  Optimal grid connections due to permanent magnet generator technology + full converter.

Complies with environmental regulations:

- Reduced visual impact.
- Noise reduction: Gamesa NRS® system and new aerodynamic blade profile.

Global capacity for production, installation and operation and maintenance

Gamesa is a company specializing in technologies for sustainable energy, mainly wind energy, and is one of the world leaders in the manufacture of wind turbines. Within this sector, Gamesa manages the entire process, from the design, manufacture and installation of wind turbines, to their operation and maintenance.

The over 24,000 MW installed throughout the world is evidence of the excellent performance of Gamesa's wind turbines. This optimum behavior is only possible with a full command of the technology and of the product with all its critical components.

Gamesa has the capacity to design, manufacture, operate and maintain its wind turbines. The tailor-made development of the critical components of its turbines -from the gearbox to the blades- ensures excellence in the design and the very highest quality standards. At the same time, it permits the shortest delivery times and the fastest technical response during the maintenance period.

Research, Development and Innovation form an integral part of the company's processes and products as well as its tasks and operations all along the supply chain, ensuring customer satisfaction and the search for excellence. In addition to this high ability to innovate, Gamesa also has a remarkable production capacity. From over 30 production centers in Europe, the United States, China, India and Brazil, Gamesa fully controls the production process and attends to the needs of its clients on all five continents, offering its customers the highest quality standards and short customer response times.

Versatile platform

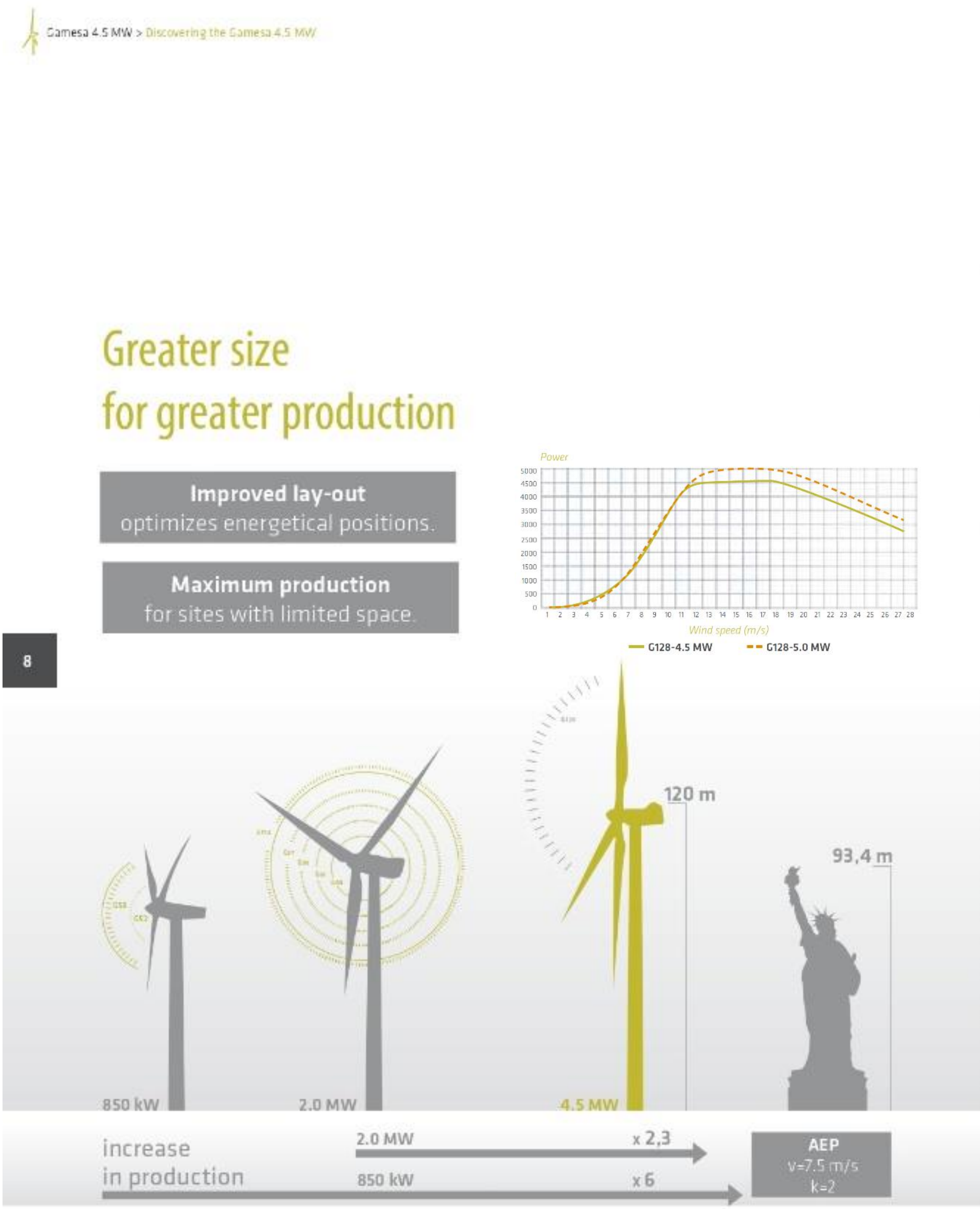
4.5 MW for low and medium winds

Gamesa has applied design and validation concepts to its new wind turbine development that are only comparable to those used in such demanding industries as the aeronautical industry, where product reliability must be assured from the first day in operation.

Gamesa 4.5 MW is the result of the evolution of Gamesa technology.

Model	G128-4.5 MW
IEC	IIA
Rated Power	4,500 kW/5,000 kW(1)
Tower Heights	81, 120, 140 m
Type Certificate	√(2)
Grid connection	√
Env. / Opt.(3)	√
50 Hz/60 Hz	√

(1) Availability depending on the site.
(2) For 60 Hz available only Design Certificate.
(3) Different versions and optional kits are available to adapt machinery to high or low temperatures and saline or dust environments.


Gamesa 4.5 MW > Discovering the Gamesa 4.5 MW
Greater size
for greater production
Improved lay-out
optimizes energetical positions.
Maximum production
for sites with limited space.
8
Power
Wind speed (m/s)
G128-4.5 MW
G128-5.0 MW
120 m
93,4 m
850 kW
2.0 MW
4.5 MW
increase
in production
2.0 MW
x 2,3
850 kW
x 6
AEP
v=7.5 m/s
k=2

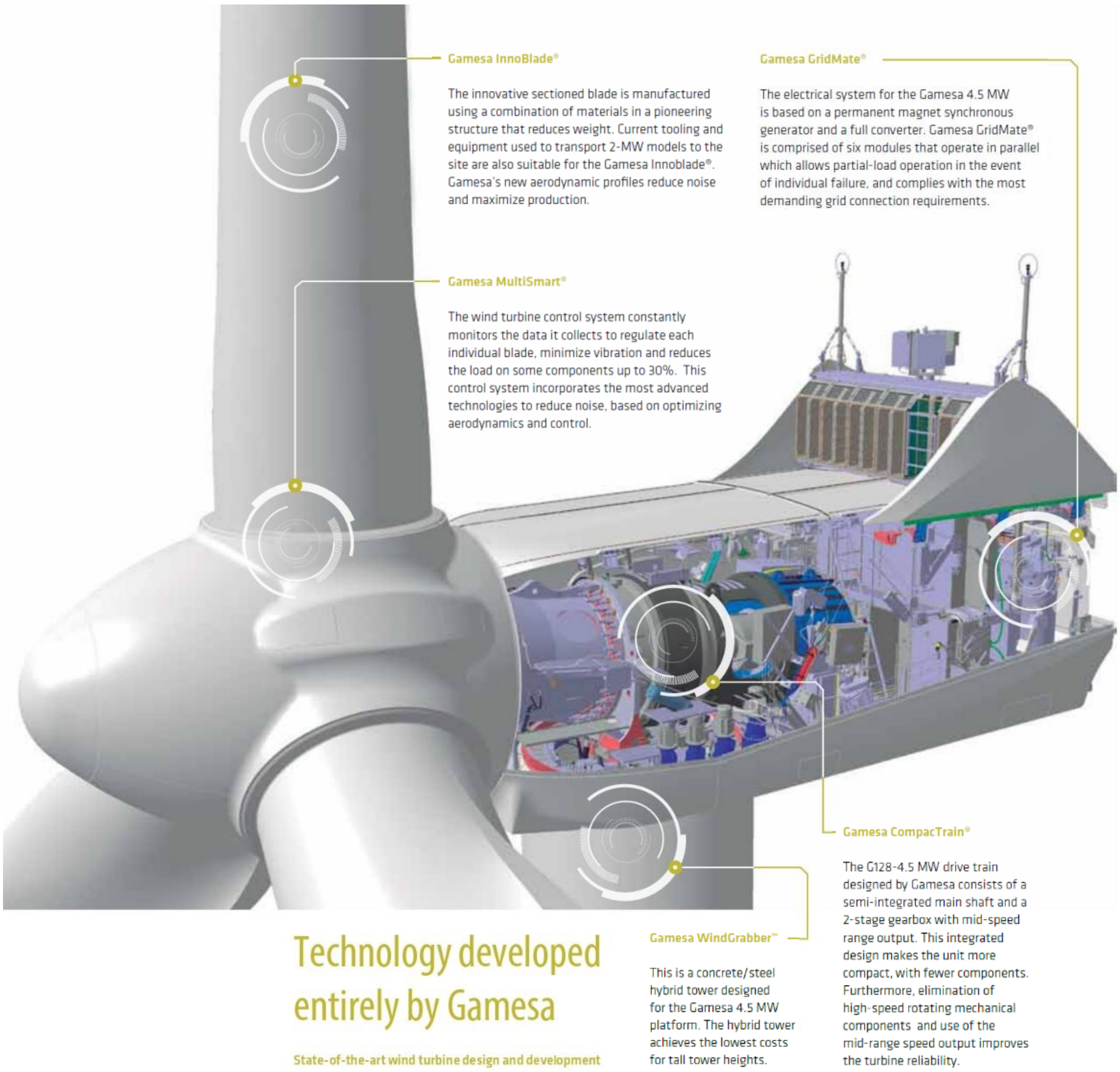
Advantages of the Gamesa 4.5 MW platform

- Individual pitch and multivariable control minimize weight, loads and noise.
- Sectional blade for easy transport and installation.
- Compact, high-performance drive train reduces mechanical stress.
- Permanent magnet synchronous generator and full converter technology that allow the most demanding grid code requirements to be met.
- Modular design of the nacelle and blades for maximum reliability and easy assembly and maintenance.
- Add-on crane attaches to nacelle for assisting in the assembly and maintenance of the main modules.
- Aerodynamic blade design and the Gamesa NRS® control system minimize noise emissions.
- Gamesa WindNet®: the advanced SCADA technology for online wind farm control and monitoring.
- Gamesa SMP System: system for predictive maintenance.

Gamesa FlexiFit®

Add-on crane, coupled to nacelle, capable of assembling the main modules.

Gamesa FlexiFit® is used for on-site assembly and servicing of large components. Its main advantage is that it is coupled to the nacelle and requires no additional external structure. In many situations, it is an alternative to the use of heavy cranes. It requires no special means of transport to be moved and consists of several modules assembled at ground level. Once Gamesa FlexiFit® is fixed to the nacelle, the main components of the wind turbine can be raised and lowered.


Gamesa InnoBlade®
The innovative sectioned blade is manufactured using a combination of materials in a pioneering structure that reduces weight. Current tooling and equipment used to transport 2-MW models to the site are also suitable for the Gamesa Innoblade®. Gamesa's new aerodynamic profiles reduce noise and maximize production.
Gamesa GridMate®
The electrical system for the Gamesa 4.5 MW is based on a permanent magnet synchronous generator and a full converter. Gamesa GridMate® is comprised of six modules that operate in parallel which allows partial-load operation in the event of individual failure, and complies with the most demanding grid connection requirements.
Gamesa MultiSmart®
The wind turbine control system constantly monitors the data it collects to regulate each individual blade, minimize vibration and reduces the load on some components up to 30%. This control system incorporates the most advanced technologies to reduce noise, based on optimizing aerodynamics and control.
Gamesa CompacTrain®
The G128-4.5 MW drive train designed by Gamesa consists of a semi-integrated main shaft and a 2-stage gearbox with mid-speed range output. This integrated design makes the unit more compact, with fewer components. Furthermore, elimination of high-speed rotating mechanical components and use of the mid-range speed output improves the turbine reliability.
Gamesa WindGrabber™
This is a concrete/steel hybrid tower designed for the Gamesa 4.5 MW platform. The hybrid tower achieves the lowest costs for tall tower heights.
Technology developed entirely by Gamesa
State-of-the-art wind turbine design and development

Gamesa

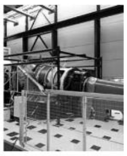
4.5 MW

Reliability brought about through a thorough program of validation checks and tests

This goal has been achieved because of an ambitious validation and testing program that has allowed the Gamesa 4.5 MW to start operating at maximum availability right from the outset:

- More than 600 tests on components of the various wind turbines in the Gamesa 4.5 MW platform were carried out at 100 certified laboratories in the United States, Japan and Europe.
- More than 190 functional and/or integration tests performed at the Wind Turbine Test Laboratory (LEA) at the National Renewable Energy Centre (CENER, Spain), one of the most highly qualified international technology centers specializing in applied research, development and promotion of renewable energies.
- More than 300,000 hours of validation and test engineering.

This extensive validation and development program has taken over 6 years. It was designed to test each component and system under real life operating conditions, in controlled environments in order to verify these components will function under the most demanding conditions.



Lower assembly and logistics cost

15

One of the key advantages of the Gamesa 4.5 MW platform is its compliance with the logistics and construction requirements of the Gamesa 2.0 MW platform. The modular design of the nacelle and blades of the Gamesa 4.5 MW means that the heaviest module does not exceed the total weight of the Gamesa 2.0 MW platform, which makes it just as easy to transport and assemble as a 2.0-MW wind turbine.

The Gamesa InnoBlade® segmented blade, patented by Gamesa, can be transported by road with no need for additional resources other than those already used for the Gamesa 2.0 MW wind turbine. The longest module is no more than 35 meters long. Furthermore, lifting the nacelle is the final step in the assembly requiring a heavy-tonnage crane. The remaining modules only require the help of a small auxiliary crane for assembly.

Simple maintenance cuts stoppage times

Predictive maintenance system

The Gamesa SMP-12, the predictive maintenance system is an essential tool for advanced detection of potential deterioration or faults in the main wind-turbine components.

Gamesa SMP-12 is the result of an analysis of a large number of wind turbines to identify the essential requirements with which a predictive maintenance system must comply:

- Continuous control of critical wind turbine components.
- Signal processing and alarm detection capacity.
- Integration in Gamesa Windnet®.
- Easy installation and maintenance.
- Low cost.

The system is designed to minimize corrective operations. Gamesa SMP system consists of a device located in the nacelle and a data-processing center, capable of processing and providing useful data about the condition of critical mechanical wind-turbine components.

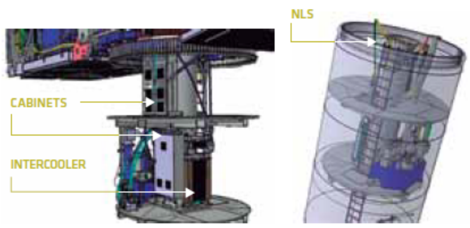
The Gamesa 4.5 MW has also been designed to take platform maintainability to a higher level by incorporating elements that optimize preventive and corrective maintenance.

Preventive maintenance

- RCM (Reliability Centered Maintenance): This reduces the time spent on preventive maintenance tasks.
- Automatic lubrication system.

Corrective maintenance:

- NLS (Nacelle Lower Structure): Nacelle lower structure allowing more space for servicing tasks to be performed.
- Easier replacement of large components: there is no need to disassemble the rotor to change the Gamesa CompacTrain®.



Optimum grid connection

The Gamesa GridMate® is the solution for the Gamesa 4.5 MW platform that assures optimum grid connection. The system uses a permanent magnet synchronous generator with independent modules and a full frequency converter. This solution allows the most demanding grid code connection requirements to be met.

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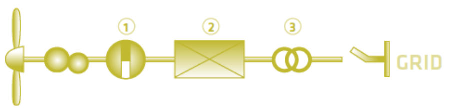
Optimum performance at variable speed at any wind speed.	**Increased production.**
De-coupling between the mechanical part and the grid, thus preventing grid disruptions from affecting the machine.	**Increased production.**
Active and reactive power control through conversion of all the power generated.	**Greater adjustment capacity.**
Improves efficiency at partial loads by optimally using the individual power modules in the converter.	**Superior output.**
Smooth connection and disconnection from the grid.	**Compliance with grid connection requirements.**



1. Multi-pole synchronous **GENERATOR** with six independent modules in parallel.
2. **CONVERTER** with six independent modules and built-in automatic circuit breaker.
3. **TRANSFORMER** with multiple grid voltage connection options.

Range of power factor:	0.9 cap / 0.9 ind
Support of 0V voltage-drop:	YES
Injection of reactive current:	YES
Adjustment of active, reactive, frequency and voltage:	YES, with Scada WindNet®

128

ROTOR	
Diameter	128 m
Swept area	12,868 m^2

BLADES	
Number of blades	3
Length	62.5 m
Material	Organic matrix composite reinforced with fiber glass or carbon fiber

TOWER	
Type	Conical tubular concrete and steel tower
Height	81, 120, 140 m

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GEAR BOX	
Type	2-stage planetary gearbox
Ratio	1:37.88

GENERATOR	
Type	Permanent magnet synchronous generator with independent modules in parallel
Nominal power	4,500 kW/5,000 kW*
Voltage	690 V AC
Frequency	50 Hz / 60 Hz
Protection class	IP 54
Rotation speed	448 rpm
Power factor	0.9 CAP - 0.9 IND **

* Availability depending on the site.
** Power factor at output terminals of the wind turbine on the low voltage side before entering the transformer, at the rated grid voltage.

Gamesa

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Printed date: November 2012

Annex G: Economic study graphhics

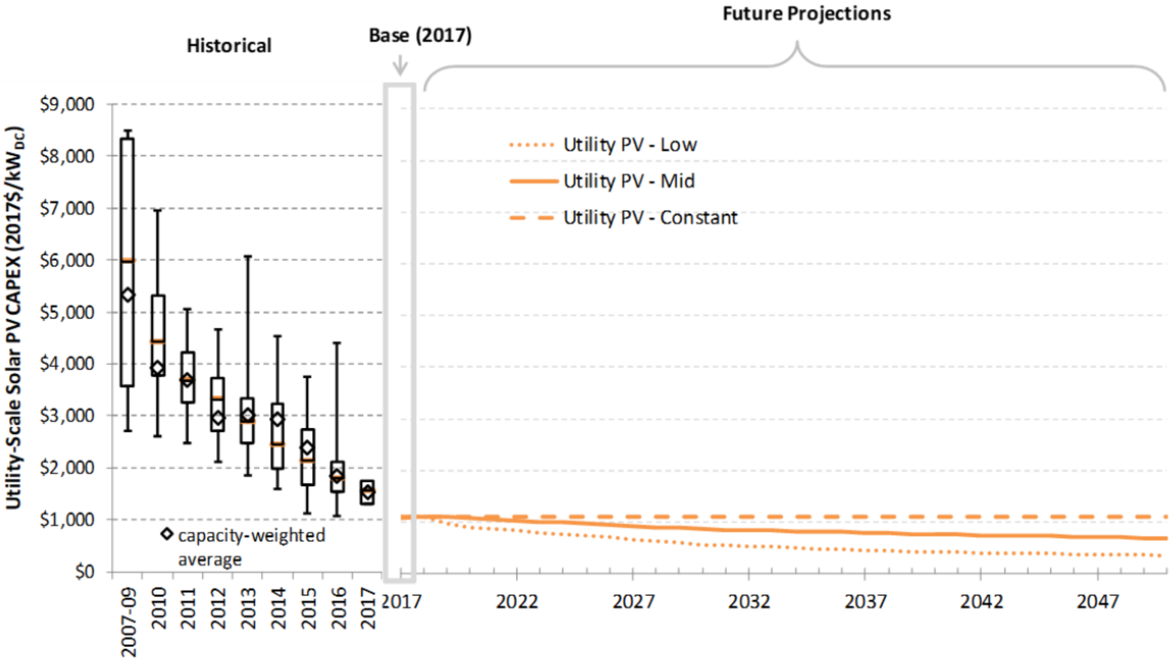

Figure A.6: Utility-scale PV CapEx historical evolution and future projections [38]

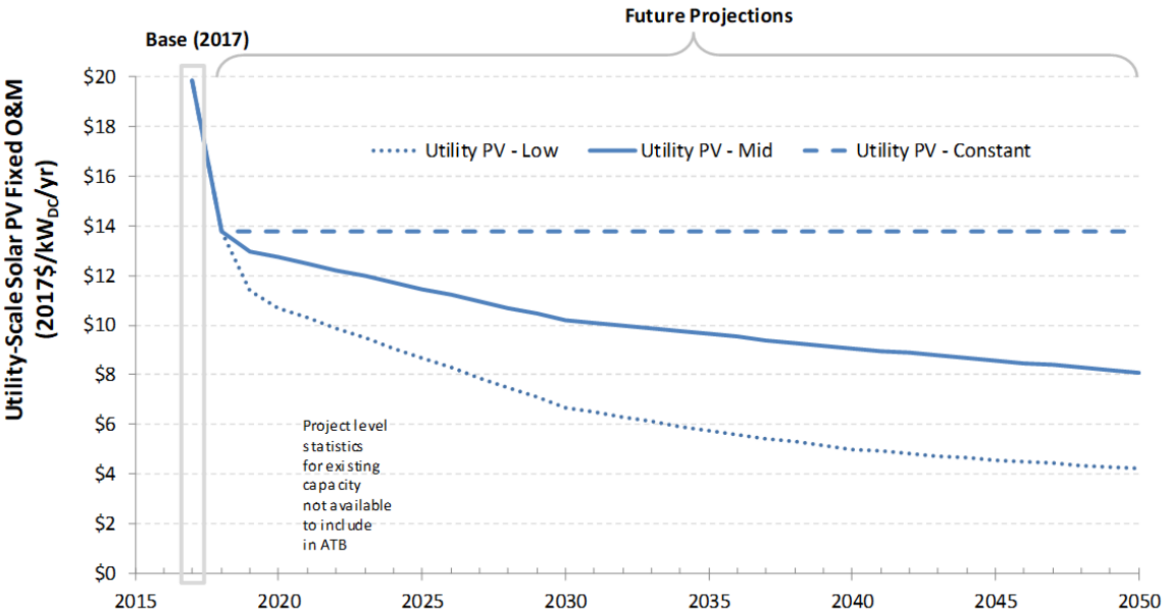

Figure A.7: Usility-scale PV OpEx future projections [38]

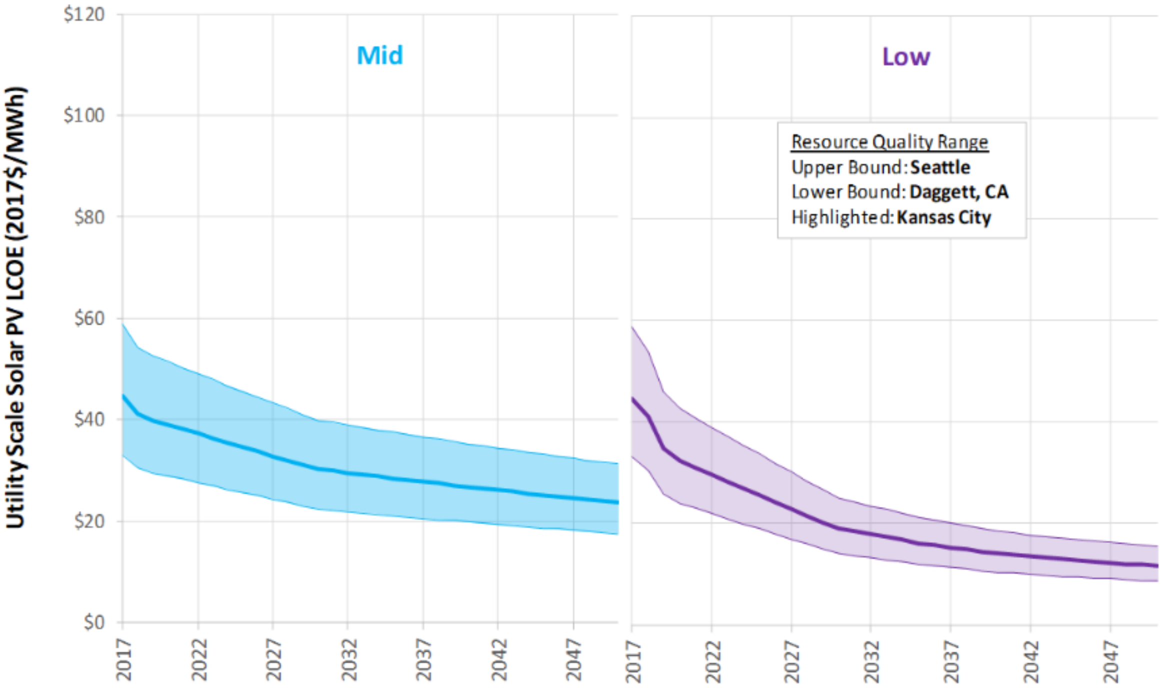

Figure A.8: Usility-scale PV LCOE future projections [38]

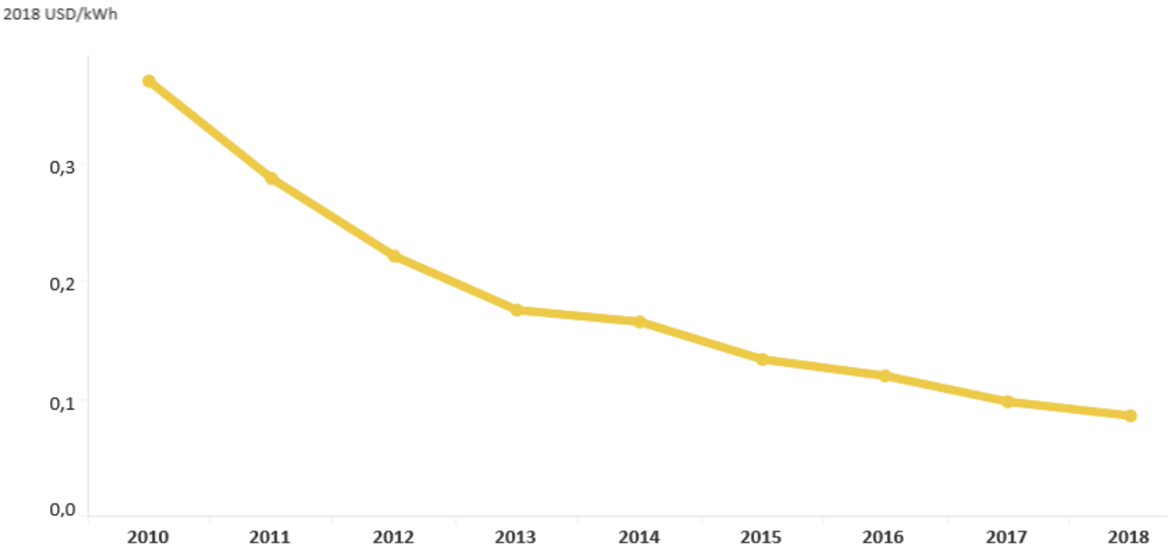

Figure A.9: Solar PV LCOE 2010-2018

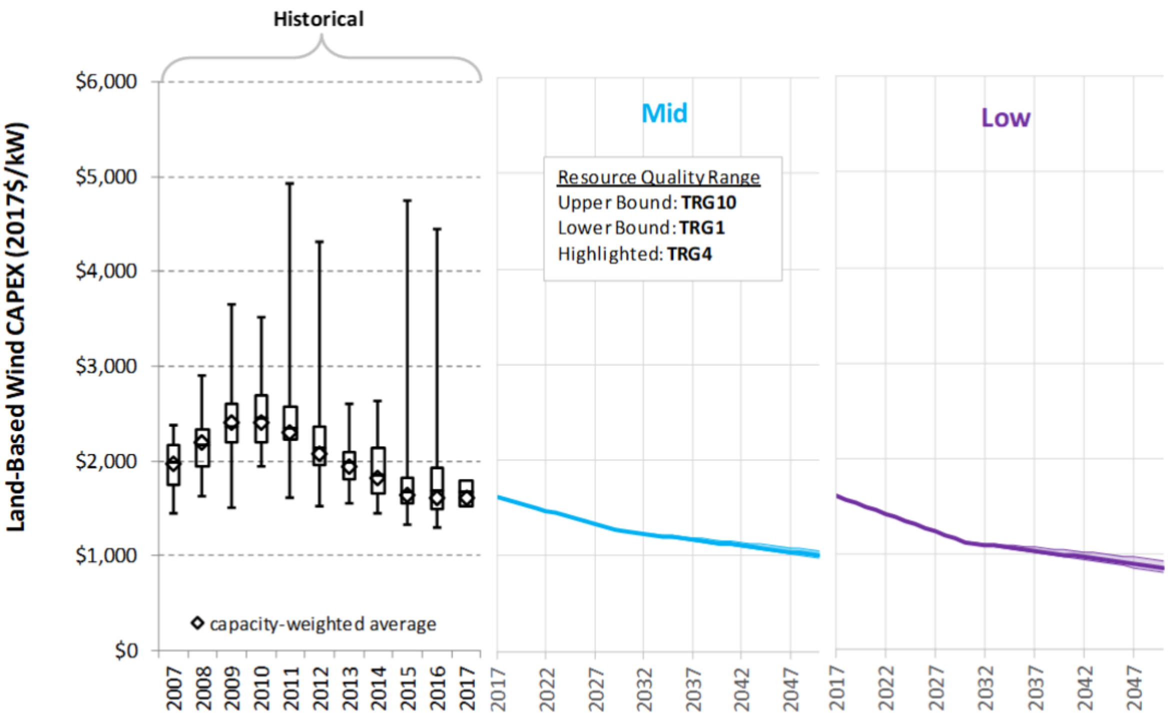

Figure A.10: Onshore wind CapEx historical evolution and future projections [38]

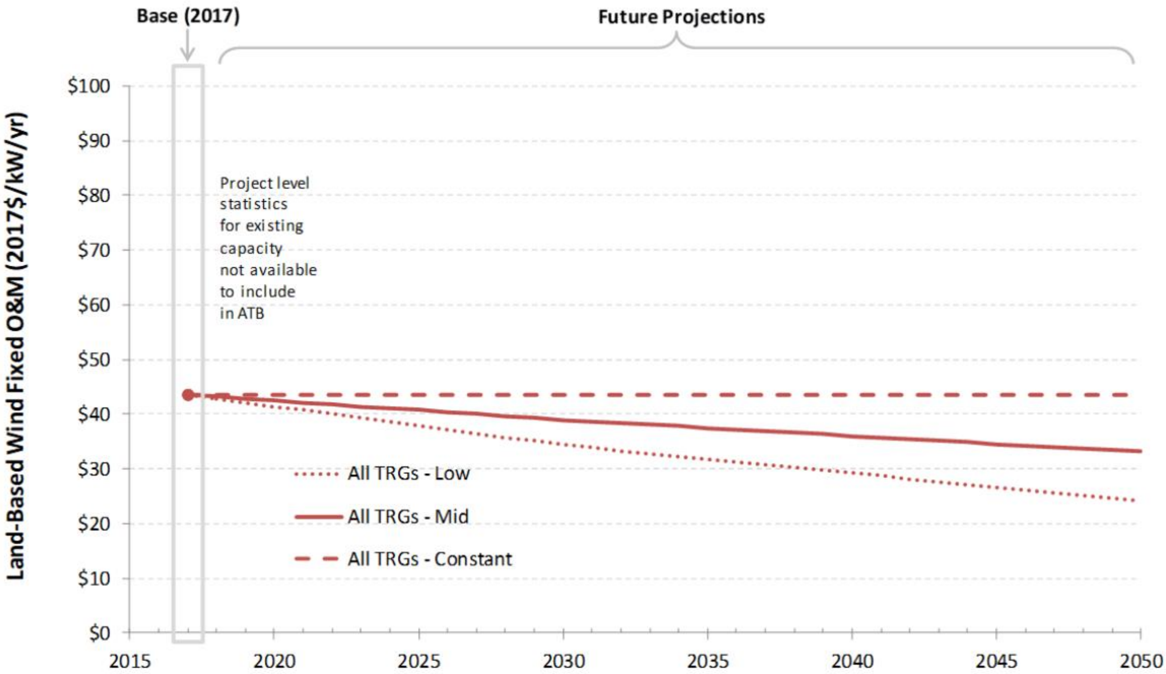

Figure A.11: Onshore wind OpEx future projections [38]

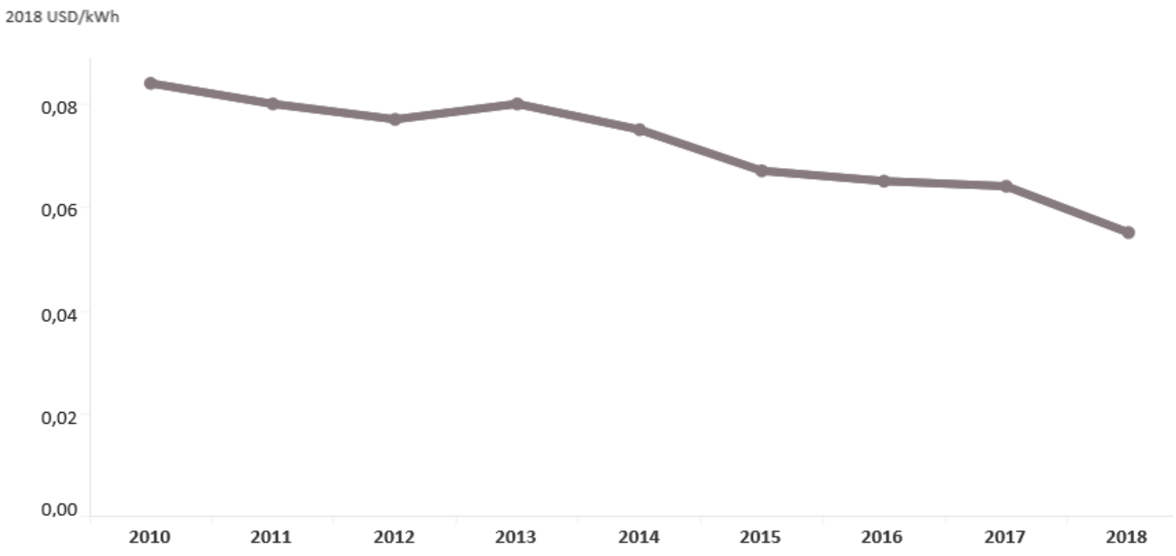

Figure A.12: Onshore wind LCOE 2010-2018 [36]

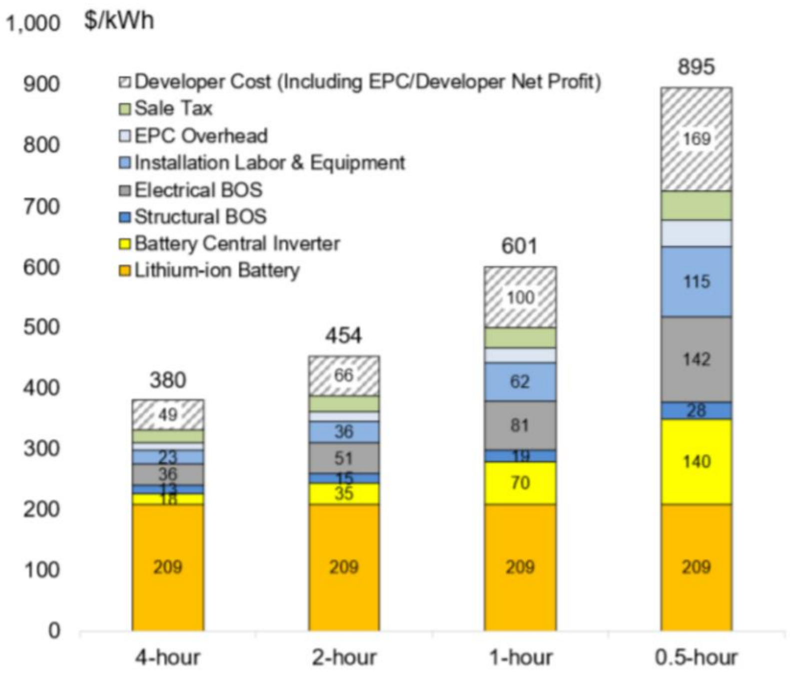

Figure A.13: 2018 U.S utility-scale Li-ion standalone storage costs [38]

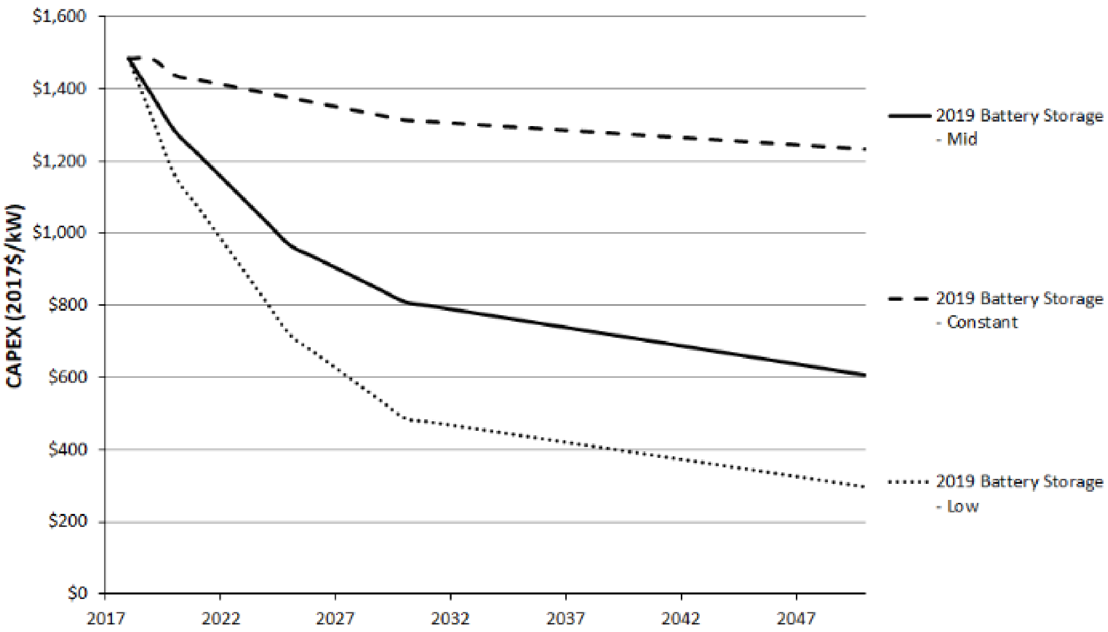

Figure A.14: Battery storage ATB cost projections [38]

Annex H: Not-supplied without batteries

```
function Not_supplied = not_supply_without_battery(nmodules,
nturbines)
% Calculates the not suplied demand
% Returns a vector where each row is an hour of the year
% nmodules = number of PV modules
% nturbines = number of wind turbines

load('Data1') % load data previously defined
Consumption = table2array(Data1(:,1)); % hourly demand in MW
Solar = table2array(Data1(:,2)); % PV generation W/kWp
Wind = table2array(Data1(:,3)); % wind power generation
kW/turbine
Total_Solar = Solar * (nmodules * 400 / 1000) / 1000000; %
total PV generation in MW
Total_Wind = Wind * nturbines / 1000; % total wind power
generation in MW
Not_supplied = Consumption - Total_Solar - Total_Wind; % not
supplied demand at each hour, in MWh
format long

end
```

Annex I: Supplied with batteries

```
function [Not_supplied_corrected,excess_total] =
not_supply_with_battery(nmodules, nturbines, battery)
% Calculates the supplied demand having into account the
batteries
% nmodules = number of PV modules
% nturbines = number of wind turbines
% battery = total battery capacity in MWh
% Not_supplied_corrected is a vector of not supplied energy
(MWh) where each row is an hour of the year
% excess_total is the amount of energy (MWh) that is "thrown
away" because it isn't used and cannot be stored in the
batteries

Not_supplied =
not_supply_without_battery(nmodules,nturbines); % not
sypplied demand for every hour in MWh, without batteries
Not_supplied_added=[Not_supplied(:);Not_supplied(1:32)]; %
first hours of the next year are added to correct the supply
later
initial = 0; % initial state of the battery ---> 0 = empty ;
1 = full
final = 0; % final state of the battery
excess_total=0; % energy that is "thrown away"
Not_supplied_with_batteries = []; % not supplied energy at
every hour

for i=1:length(Not_supplied_added)
    Not_supplied_without = Not_supplied_added(i);
    if Not_supplied_without > 0 % if at this particular time
not enough energy is generated to supply the demand
        if initial == 0 % if the battery is empty
            Not_supplied_with = Not_supplied_without; % the
not-supplied energy remains the same
            final = 0; % and the battery remains empty
        else % if the battery has some energy stored
            if Not_supplied_without > initial % if it is
needed more power than the stored in the battery
                Not_supplied_with = Not_supplied_without -
initial;
                final = 0; % the battery supplies all the
stored energy
            else % if the battery has more stored energy than
needed
                Not_supplied_with = 0;
                final = initial - Not_supplied_without; % the
battery supplied the needed energy
```

```
            end
        end
    else % Not_supplied_without < 0 ---> if at this
particular time it is generated more energy than needed to
supply the demand
        excess1 = - Not_supplied_without; % excess of energy
generated (generated - demand)
        Not_supplied_with = 0; % all necessary energy is
supplied
        if initial < battery % if the battery is only
partially charged
            if (initial + excess1) < battery % the battery
can be charged with all excess generation
                final = initial + excess1;
            else % the battery is charged to the maximum and
there is still energy left
                final = battery;
                excess_total = excess_total + excess1 -
(battery - initial); % the energy that can't be stored in the
battery is "thrown away"
            end
        else % if the battery is already full
            final = initial;
            excess_total = excess_total + excess1; % all
exceeding energy generated is "thrown away"
        end
    end
initial = final; % initialize the state of the battery for
the next hour
Not_supplied_with_batteries = [Not_supplied_with_batteries(:)
; Not_supplied_with]; % not supplied demand is updated
end

Not_supplied_corrected =
[Not_supplied_with_batteries(8761:end) ;
Not_supplied_with_batteries(33:8760)]; % first hours of the
year are corrected with the objective of obtaining  cyclical
data

end
```

Annex J: Summary supplied

```
function
[Renewables_supply,Non_renewables_supply,Annual_consumption,r
enewable_percentage,excess_total,Non_renewables_power] =
supply(nmodules,nturbines,battery)
% Summary of supply data
% nmodules = number of PV modules
% nturbines = number of wind turbines
% battery = total battery capacity in MWh
% Renewables_supply
% Non_renewables_supply
% Annual_consumption
% renewable_percentage


load('Data1')
Consumption = table2array(Data1(:,1)); % hourly demand in MW
Annual_consumption=sum(Consumption);

[Not_supplied_corrected,excess_total] =
not_supply_with_battery(nmodules, nturbines, battery);
% excess_total is the amount of energy that is "thrown away"
because it isn't used and cannot be stored in the batteries
Non_renewables_supply = sum(Not_supplied_corrected); % annual
amount of non-renewable energy required to supply all
consumption, in MWh
Non_renewables_power = max(Not_supplied_corrected); % the
amount of power needed from non-renewable sources
Renewables_supply = Annual_consumption -
Non_renewables_supply; % annual amount of renewable energy
supplied, in MWh
renewable_percentage = Renewables_supply / Annual_consumption
* 100; % percentage of renewable energy supplied

end
```

Annex K: Justification OpEx battery

With life expectancy from the selected devices:

	CapEx (€/kW)	OpEx (€/kW*year)	Lifetime (years)	Total cost for the lifetime (€/kW)	Total cost for one year (€/kW)
Battery	391.18	9.1	10	482.18	48.018
PV energy	1337.5	21	23	1862.5	74.5
Wind energy	1429	39.18	23	2330.14	101.31
Diesel	819	27.755	23	1457.37	63.36
Cable	2800	120.4	45	8218	182.62

Table 15: CapEx and OpEx for life expectancy from the selected devices

With N=20 (total costs increases 10%):

	CapEx (€/kW)	OpEx (€/kW*year)	Lifetime (years)	Total cost for the lifetime (€/kW)	Total cost for one year (€/kW)
Battery	391.18	33.67	20	1064.58	53.229
PV energy	1337.5	21	20	1757.5	87.875
Wind energy	1429	39.18	20	2212.6	110.63
Diesel	819	27.755	20	1374.1	68.705
Cable	1400	120.4	20	3808	190.4

Table 16: CapEx and OpEx for life expectancy of 20 years

Annex L: $LCOE_m$ calculation programms

$LCOE_m$ only renewables

```
function LCOEmod =
LCOEmod_renewables(nmodules,nturbines,battery)
% Calculates the LCOEmod (€/MWh) if only renewable sources
are taken into account
% nmodules = number of PV modules
% nturbines = number of wind turbines
% battery = total battery capacity in MWh

CapEx_PV = 537 * nmodules;
CapEx_wind = 6430500 * nturbines;
CapEx_battery = 391180 * battery;
CapEx_total = CapEx_PV + CapEx_wind + CapEx_battery;
n = 20; % power system lifetime
OpEx_PV = 8.4 * nmodules;
OpEx_wind = 176310 * nturbines;
OpEx_battery = 33670 * battery;
OpEx_total = OpEx_PV + OpEx_wind + OpEx_battery;
[Renewables_supply,Non_renewables_supply,Annual_consumption,r
enewable_percentage] = supply(nmodules,nturbines,battery);
LCOEmod = (CapEx_total / n + OpEx_total) / Renewables_supply;

end
```

$LCOE_m$ renewables and fuel

```
function LCOEmod = LCOEmod_fuel(nmodules,nturbines,battery)
% Calculated the LCOEmod if the demand is supplied with
renewables and fuel
% nmodules = number of PV modules
% nturbines = number of wind turbines
% battery = total battery capacity in MWh

[Renewables_supply,Non_renewables_supply,Annual_consumption,r
enewable_percentage, excess_total,Non_renewables_power] =
supply(nmodules,nturbines,battery);
CapEx_PV = 537 * nmodules;
CapEx_wind = 6430500 * nturbines;
CapEx_battery = 391180 * battery;
CapEx_fuel = 819 * 1000 * Non_renewables_power;
CapEx_total = CapEx_PV + CapEx_wind + CapEx_battery +
CapEx_fuel;
n = 20; % power system lifetime
OpEx_PV = 8.4 * nmodules;
OpEx_wind = 176310 * nturbines;
OpEx_battery = 33670 * battery;
OpEx_fuel = 27.755 * 1000 * Non_renewables_power;
OpEx_total = OpEx_PV + OpEx_wind + OpEx_battery + OpEx_fuel;
Fuel_cost = 313 * Non_renewables_supply;
LCOEmod = (CapEx_total / n + OpEx_total + Fuel_cost) /
Annual_consumption;

end
```

$LCOE_m$ renewables and cable

```
function LCOEmod = LCOEmod_cable(nmodules,nturbines,battery)
% Calculated the LCOEmod if the demand is supplied with
renewables and fuel
% nmodules = number of PV modules
% nturbines = number of wind turbines
% battery = total battery capacity in MWh

[Renewables_supply,Non_renewables_supply,Annual_consumption,r
enewable_percentage,excess_total,Non_renewables_power] =
supply(nmodules,nturbines,battery);

CapEx_PV = 537 * nmodules;
CapEx_wind = 6430500 * nturbines;
CapEx_battery = 391180 * battery;
CapEx_cable = 1400000 * Non_renewables_power;
CapEx_total = CapEx_PV + CapEx_wind + CapEx_battery +
CapEx_cable;
n = 20; % power system lifetime
OpEx_PV = 8.4 * nmodules;
OpEx_wind = 176310 * nturbines;
OpEx_battery = 33670 * battery;
OpEx_cable = 120400 * Non_renewables_power;
OpEx_total = OpEx_PV + OpEx_wind + OpEx_battery + OpEx_cable;
Energy_cost = 45 * Non_renewables_supply;
LCOEmod = (CapEx_total / n + OpEx_total + Energy_cost) /
Annual_consumption;

end
```

Annex M: Optimization and simulation program

```
function [Result,opt] = simulation()
% mesh to simulate
modules = 5000:50000:1305000; % 27 combinations
turbines = 2:20:122; % 7 combinations
batteries = 10:200:2010; % 11 combinations

% variables to store the results
V_modules = []; % vector with the number of PV modules at
each iteration
V_turbines = [];
V_batteries = [];
V_renewable_percentage = []; % vector with the percentage of
renewable supply
V_lcoe = []; % vector with the lcoe_mod
V_ratio = []; % vector with the ratio
V_excess = [];

% optimum value
nmodules_opt = 0;
nturbines_opt = 0;
battery_opt = 0;
renewable_perc_opt = 0;
LCOEmod_opt = 100000000;
ratio_opt = 100000000;
excess_opt = 0;


for i_modules = 1:length(modules)
    nmodules = modules(i_modules);
    for i_turbines = 1:length(turbines)
        nturbines = turbines(i_turbines);
        for i_batteries = 1:length(batteries)
            battery = batteries(i_batteries);


[Renewables_supply,Non_renewables_supply,Annual_consumption,r
enewable_percentage,excess_total,Non_renewables_power] =
supply(nmodules,nturbines,battery);
            LCOEmod =
LCOEmod_renewables(nmodules,nturbines,battery);
            ratio = LCOEmod / renewable_percentage; % ratio
to minimize

            V_modules = [V_modules ; nmodules];
            V_turbines = [V_turbines ; nturbines];
            V_batteries = [V_batteries ; battery];
```

```
            V_renewable_percentage = [V_renewable_percentage
; renewable_percentage];
            V_lcoe = [V_lcoe ; LCOEmod];
            V_ratio = [V_ratio ; ratio];
            V_excess = [V_excess ; excess_total];

            if ratio < ratio_opt
                nmodules_opt = nmodules;
                nturbines_opt = nturbines;
                battery_opt = battery;
                renewable_perc_opt = renewable_percentage;
                LCOEmod_opt = LCOEmod;
                ratio_opt = ratio;
                excess_opt = excess_total;
            end
        end
    end
end

% Matlab results
Result = [V_modules , V_turbines , V_batteries ,
V_renewable_percentage , V_lcoe , V_ratio , V_excess];
opt = [nmodules_opt , nturbines_opt , battery_opt ,
renewable_perc_opt , LCOEmod_opt , ratio_opt , excess_opt];

% Store results in an excel
Resultat=array2table(Result);
filename = 'prova.xlsx';
writetable(Resultat,filename,'Sheet',1,'Range','A1')

end
```